U.S. Geological Survey Earthquake Hazards Reduction Program
Final Technical Report

Estimating Uncertainties of Seismic Hazard Parameters for Nevada Faults, Formations of a Nevada Quaternary Fault Working Group, and Gaining Consensus Fault Parameters

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Abstract

Twenty-two nationally recognized scientists, known as the Nevada Quaternary Fault Working Group, assembled and reviewed the current status of research on several of Nevada's high risk faults, recommended seismic hazard values for faults when possible, and recommended future directions of research on major faults in Nevada. The Working Group met for two days in Reno and reviewed twelve of Nevada's high-risk faults. Background reports for each fault were distributed to the scientists before the meeting. At the meeting each fault was reviewed, including relevant reports and studies, any known paleoearthquake history, estimated fault slip rates, estimated earthquake recurrence intervals, earthquake segmentation models, and estimated single-event displacements.

The working group found that Nevada was still in the early stages of characterizing most of its high-risk faults, and more research and age determinations are needed to constrain seismic hazard parameters. Consequently, it was difficult for the group to determine many consensus fault parameters. The working group did, however, make a series of recommendations to help gain more information so that consensus values can be attained in the future. A follow-up meeting was strongly recommended by the group to review other high risk faults in Nevada, prioritize faults to be studied, and continue making recommendations for important studies. The initial recommendations presented here were developed at the meeting and reviewed by several working group members following the meeting.

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Introduction

The Nevada Quaternary Fault Working Group was established to 1) critically evaluate the accuracy and completeness of the paleoseismic-trenching data, particularly with regard to earthquake timing, displacements, and fault slip rate, 2) assign consensus, preferred recurrence interval and vertical slip rate estimates with appropriate confidence limits to the faults reviewed, where the data is adequate to do so, and 3) identify critical gaps in the paleoseismic data and recommend where and what kinds of additional studies that should be performed to ensure Nevada's earthquake hazard is adequately documented and understood.

The Working Group members are:

Nevada

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Ivan Wong	URS

The Working Group convened in mid-November 2007 to review and assess the accuracy and completeness of the paleoseismic data available for eleven high-risk faults, and to make recommendations for additional research necessary to adequately understand and characterize these faults. The faults reviewed were:

Reno-Carson City Urban Corridor

- Genoa fault
- Carson City fault
- Kings Canyon fault zone
- Indian Hill fault zone
- Mt. Rose fault zone
- Peavine Peak fault
- Olinghouse fault zone
- Pyramid Lake fault zone
- Warm Springs Valley fault system

Las Vegas Urban Area

- Las Vegas Valley fault system
- Eglington fault (part of the Las Vegas Valley fault system)
- Black Hills fault zone

This report includes the agenda of the working group meeting, the edited initial recommendations, and the background reports for the twelve faults that were supplied to the Working Group.

Nevada Quaternary Faults Working Group Meeting
AGENDA

November 19, 2007

8:00 Introduction, Agenda, and Purpose (dePolo)
8:10 Introduction and Purpose (USGS)
8:30 Utah Working Group Experience (Lund)
8:40 Estimating Two-Sigma Ranges and Uncertainties (Wong)
8:50 Goals, Approach, and Questions (dePolo)

9:00 Carson Range fault system Overview
9:05 Genoa fault

10:15 - BREAK -

10:45 Genoa fault (cont.)
11:00 Carson City faults (Carson City fault, Kings Canyon fault zone, and Indian Hill fault zone)

12:00 - LUNCH -

1:00 Mt. Rose fault zone
2:10 Carson Range fault system Earthquake Segmentation

2:30 - BREAK -

3:00 Peavine Peak fault
4:00 Las Vegas Valley fault system
5:00 Wrap-Up and Outstanding Issues

5:30 - ADJOURN -

November 20, 2007

8:00 Eglington fault
9:00 Black Hills fault

10:00 - BREAK -

10:30 Pyramid Lake fault zone

12:00 - LUNCH -

1:00 Warm Springs Valley fault system
2:00 Olinghouse fault zone

2:30 - BREAK -

3:00 Olinghouse fault zone (cont.)
3:30 Planning Special Consideration Zones
3:45 Prioritizing Identified Earthquake Research
4:15 Prioritizing the Next Faults for the Working Group to Review
4:30 Wrap-Up and Outstanding Issues

5:00 - ADJOURN -

Nevada Quaternary Fault Working Group
Initial Recommendations for Research Priorities for studies of Quaternary Fault in Nevada

The level of knowledge needed to reasonably characterize the large hazard and risk associated with Nevada's major active faults is inadequate and requires an aggressive effort to acquire the geoscience data necessary to evaluate the seismic hazard to Nevada's urban centers. These data can then be used by scientists, planners, and government officials to aid in adopting practices appropriate to enhance the safety of Nevada's citizens.

These are termed "initial recommendations" because a follow-up meeting is needed to further debate, refine, eliminate, and add to these comments. Divergent views exist among the Working Group members on the relative importance of some of these ideas. Further discussion is needed before these recommendations can be prioritized, and there are other high-risk faults in Nevada that need to be reviewed by the Working Group to explore whether there are additional recommendations.

Planning Special Consideration Zones

The State of Nevada should develop a strategy to create Planning Special Consideration Zones that will allow for safe development with respect to potentially hazardous earthquake faults. With input from design, engineering, and geoscience professionals, the creation of these zones will guide land-use planners, building officials, and developers in minimizing the adverse effects of fault surface rupture and other earthquake-related hazards. The late Quaternary faults in Nevada urban areas should then be mapped and zoned at a scale of 1:24,000 using the developed strategy.

Northern Nevada

General Needs for Northern Nevada

Abundant information related to late Quaternary faulting and surface ruptures likely exists in a variety of unpublished reports and documents prepared by consultants and construction firms in the Reno-Carson City urban corridor. The contents of these reports could provide new insight into the activity rates or ages of surface ruptures on various fault zones or strands. The working group recommends that an effort be made to systematically poll geoscience consultants in the area, and to collect and archive non-proprietary reports that contain information relevant to fault activity and related hazards. This archive should be based at a state agency where the information will be publicly available.

Mt. Rose fault zone

The Mt. Rose fault zone includes the Washoe Valley fault zone, the Little Valley fault, and the Virginia Lake fault zone.

Currently available paleoseismic data are inadequate to characterize the times of prehistoric large earthquakes along the fault zone. The close proximity of this fault system to the Reno-Carson City urban centers makes its study a priority.

The only compelling constrains on paleoearthquakes on the Mt. Rose fault zone from existing data are that two surface-rupturing earthquakes have occurred since about 1,553-1,862 cal. yr BP. Geological and geophysical studies are needed to develop paleoseismic records of earthquakes for the major strands of the zone. These records can be developed by first systematically mapping of fault strands and determining the ages of various faulted deposits. These studies can yield valuable information about long-term slip rates and the time of the most recent event. Geophysical and subsurface studies may be helpful in defining the down-dip and along-strike links between various strands. Eventually, trenching studies at selected sites will be required to define critical parameters such as displacement per event, the times of prehistoric surface-faulting earthquakes, and short-term fault slip rates.

Recommended studies include:

1. Systematically conduct detailed geologic mapping of fault strands and deposits to determine the age of offset deposits, to estimate slip rates, and to identify future trenching sites.

2. Conduct geophysical and subsurface studies to determine fault dips (a parameter in calculating fault slip rates) and along-strike intersections and likages to help evaluate segmentation models and understand when slip might be distributed across multiple, parallel fault strands.

Genoa fault

The Genoa fault is one of the most active faults threatening the Reno-Carson City urban corridor. Initial trenching studies at selected sites have yielded helpful information, but given the potential hazard it poses, the Genoa fault should be the target of significant additional studies in the immediate future. The key firm conclusion that results from studies conducted to date is that two large earthquakes have produced surface rupture on the Genoa fault within the past 1,800 years. To fully evaluate the hazard associated with the Genoa fault, we need better information about the ages of recent large paleoearthquakes, particularly the penultimate and antepenultimate events. Glacial deposits and surfaces that are offset across the Geona fault should be further studied for fault slip rate information.

Given the information and samples available from preceding studies, we recommend the following specific tasks:

1. Use the OxCal radiocarbon calibration program (http://c14.arch.ox.ac.uk/embed.php?File=oxcal.html), to evaluate the radiocarbon ages currently available for the Genoa fault to help reduce uncertainties in the ages of the two recognized prehistoric events. In the analysis of the ages of the Jacks Valley study, include the "390-year age", and consider the beginning of the historical record, 1850, as the limiting constraint for the youngest age of the most recent event.
2. Submit additional radiocarbon samples from existing trenching studies for analysis to reconfirm ages and/or the hypotheses derived from original age determinations.
3. Construct a detailed topographic and geologic map of the outwash terraces at the Woodfords site and accurately measure the vertical offset across the fault on deposits of different ages. Undertake studies to more accurately date the outwash terraces using a variety of age-determination techniques. Identify potential trench sites that have the potential to better define the history of earthquakes that have offset the terraces.
4. Evaluate the feasibility of: a) excavating a mega-trench, b) collecting high-resolution seismic-reflection data, and/or c) conducting a shallow drilling program to develop a long-term paleoseismic record for the central part of Genoa fault. Determine if potential sites exist that might yield a long paleoseismic record (more than two events) on the central section using standard trenching methods.

Carson City fault

The Working Group concurs with the current representation of the Carson City fault in the USGS National Seismic Hazard Maps, which models the fault zone as having a 75% probability of rupturing with the Genoa fault and a 25% probability of rupturing independently. This adequately characterizes the fault's seismic hazard given the limited currently available data, however, additional studies are needed to evaluate this model of fault interactions.

Recommended studies include:

1. Conduct additional detailed geologic mapping and collect paleoseismic data for the Carson City fault to better define the temporal relations between surface ruptures on it and the Genoa fault. Long-term paleoseismic records will better define the level of independence between the two faults, as well as better characterize the seismic potential of the Carson City fault.

Kings Canyon fault zone

The Working Group concurs with the current representation of the Kings Canyon fault zone in the USGS National Seismic Hazard Maps, which models the fault zone as having a 75% probability of rupturing with the Genoa fault and a 25% probability of rupturing independently. This adequately characterizes the fault's seismic hazard given the limited currently available data, however, additional studies are needed to evaluate this model of fault interactions.

Recommended studies include:

1. Conduct additional detailed geologic mapping and collect paleoseismic data for the Kings Canyon fault zone to better define the temporal relations between surface ruptures on it and the Genoa fault. Long-term paleoseismic records will better define the level of independence between the two faults, as well as better characterize the seismic potential of the Kings Canyon fault zone.

Indian Hill fault zone

The Working Group concurs with the current representation of the Indian Hill fault zone in the USGS National Seismic Hazard Maps, which models the fault zone as having a 75% probability of rupturing with the Genoa fault and a 25% probability of rupturing independently. This adequately characterizes the fault's seismic hazard given the limited currently available data, however, additional studies are needed to evaluate this model of fault interactions.

Recommended studies include:

1. Conduct additional detailed geologic mapping and collect paleoseismic data for the Indian Hill fault zone to better define the temporal relations between surface ruptures on it and the Genoa fault. Long-term paleoseismic records will better define the level of independence between the two faults, as well as better characterize the seismic potential of the Indian Hill fault zone.

Peavine Peak fault

The Peavine Peak fault is a major active fault in the northern part of the Reno-Carson City urban corridor. The fault has been shown by recent trenching to have had as many as four to five surface-rupturing events in the Holocene (~11,500 years), but the times of these events are poorly constrained.

Recommended studies include:

1. Recollect samples from the open trenches for radiocarbon analysis to better constrain the times of individual events.

Southern Nevada

Las Vegas Valley fault system

Understanding the seismic hazards associated with faults in the Las Vegas region is especially challenging and complex because urbanization has extensively modified most of the surface features and because many of the features could be multi-genetic, that is, originate from tectonic and non-tectonic processes. Even though the true origin of many features in the Las Vegas Valley remains unclear, these structures should be considered as potential earthquake sources, and they need to be further investigated to evaluate their seismic potential. Structures in the Las Valley fault system include the Eglington, the Decatur, the Valley View, the Cashman Field, and the Whitney Mesa faults.

Recommended studies include:

1. If undeveloped, suitable sites are available, trench the faults in the system to begin developing a history of paleoearthquakes on the Las Vegas Valley fault system and the Frenchman Mountain fault. Rapid urbanization in the Las Vegas Valley limits the opportunities for these kinds of studies, but this work should be a priority while sites remain available.
2. Conduct high-resolution seismic surveys and combine information from these surveys with drill-hole data to define the geometry, amount and age of vertical offsets on faults within the system. Also, use these data as possible sources of information regarding paleoearthquakes, such as identifying buried colluvial wedges.
3. Use shallow seismic methods and drilling to better determine the offsets of deposits across faults for slip rate determinations.
4. Apply geophysical methods and combine with existing data to better define the structural relations between individual strands of the Las Vegas Valley fault system, the Las Vegas Valley shear zone, and the Frenchman Mountain fault.

Black Hills fault zone

The Black Hills fault zone is an enigmatic range-front structure with a distinct, but very short, Holocene scarp. Recent mapping suggests that the zone consists of a network of subparallel strands, but few of the strands have significant expression in the topography. Furthermore, a long trench across the main scarp exposes a complex set of faults, most of which have small vertical displacements. This pattern of faulting is unusual and atypical of most range-front faults. This trenching study found evidence for five surface-faulting events, but the interpretation of these events is non-unique.

Recommended future studies include:

1. Develop a long topographic profile across the southern parts of the Black Hills fault zone to detect possible evidence of warping or other signs of deformation that might be related to late Quaternary movement.
2. Conduct further age determinations of carbonate rinds on rock clasts collected from trench and other exposures to assess the timing of earthquakes and estimate fault slip rates.

Values Used by USGS in the 2002 National Seismic Hazard Map Database

Fault Name	Fault Slip Rate	Fault Dip	Fault Length	Earthquake Magnitude[3]	Earthquake Occurrence Rate	Average Earthquake Recur. Int.	Earthquake Segment Scenario
Black Hills f	0.41 m/ky	50º	9 km	M 6.2	1.32E-03	758 y	single
Carson City f	0.1 m/ky	50º	20 km	M 6.5	2.11E-04	4,739 y	25% w/Genoa
Eglington f	0.1 m/ky	50º	11 km	M 6.3	7.14E-05[1]	14,006 y	50% seismic
Genoa f[2]	2 m/ky	50º	53 km	M 7.1	1.75E-03	571 y	75% multiple
Indian Hill f	0.1 m/ky	50º	8 km	M 6.1	3.53E-04	2,833 y	25% w/Genoa
Kings Canyon f	0.2 m/ky	50º	18 km	M 6.5	3.97E-04	2,519 y	25% w/Genoa
Las Vegas f	[not used]						
Mt. Rose f	1.5 m/ky	50º	36 km	M 6.9	1.71E-03	585 y	single
Olinghouse f	[not used]						
Peavine Peak f	0.5 m/ky	50º	13 km	M 6.4	8.33E-03	1,200 y[1]	single
Pyramid Lake f	2 m/ky	50º	77 km	M 7.3	7.71E-04	1,297 y	single
Warm Springs f	0.5 m/ky	50º	38 km	M 6.9	3.20E-04	3,125 y	single

1 – recurrence rate assigned based on geologic evidence
2 – labeled “Carson Range fault” in database
3 – Earthquake magnitude is rounded to the nearest tenth

Radiocarbon Dates –
Nevada Quaternary Fault Working Group

Genoa fault

Table of Calibrated Dates that Relate to PE1

Sample #	Material	Pre/Post PE1	Radiocarbon date	Analysis	Calendar-Corrected Dates* 1-sigma range	2-sigma range
JV-9-3	char.	post-event	580 ±110 ybp	conv.	523 – 657 cal ybp	326 – 732 cal ybp
JV-8-4	char.	pre-event	525 ±120 ybp	conv.	476 – 660 cal ybp	308 – 683 cal ybp
JV-8-2	char.	pre-event	755 ±100 ybp	conv.	565 – 787 cal ybp	548 – 907 cal ybp
ST-5	char	post-event	580 ±115 ybp	conv.	519 – 660 cal ybp	320 – 734 cal ybp

JV = Jacks Valley site; ST = Sturgis site
* Stuiver and Reimer (1993) and Reimer and others (2004)

Table of Calibrated Dates that Relate to PE2

Sample #	Material	Pre/Post PE2	Radiocarbon date	Analysis	Calendar-Corrected Dates* 1-sigma range	2-sigma range
JV-1-1	char.	post-event(?)	2,100 ±125 ybp	conv.	1,930 – 2,302 cal ybp	1,742 – 2,352 cal ybp
ST-16	char.	post-event	1,815 ±90 ybp	conv.	1,624 – 1,865 cal ybp	1,535 – 1,933 cal ybp
ST-14	char.	pre-event	2,290 ±110 ybp	conv.	2,146 – 2,460 cal ybp	2,009 – 2,703 cal ybp

JV = Jacks Valley site; ST = Sturgis site
* Stuiver and Reimer (1993) and Reimer and others (2004)

Carson City fault

Table of Calibrated Dates that Relate to PE1

Sample #	Material	Pre/Post PE1	Radiocarbon date	Analysis	Calendar-Corrected Dates* 1-sigma range	2-sigma range
CH3	char.	pre-event/ff	390 ±40	AMS?	333 – 505 cal ybp	316 – 513 cal ybp

ff – fissure fill
* Stuiver and Reimer (1993) and Reimer and others (2004)

Table of Calibrated Dates that Relate to PE2

Sample #	Material	Pre/Post PE2	Radiocarbon date	Analysis	Calendar-Corrected Dates* 2-sigma range
CH5	bulk	pre-event	2,590 ±130	AMS?	2,348 – 2,953 cal ybp

* Stuiver and Reimer (1993) and Reimer and others (2004)

Mt. Rose fault zone

Calibrated Dates that Relate to PE1

Sample #	Material	Pre/Post	Radiocarbon Date	Analysis	Calibrated Dates* 1-Sigma Range	Calibrated Dates* 2-Sigma Range
WC-T1	bulk	pre/ff	910 ±70 ybp	conv.	770 – 913 cal ybp	691 – 934 cal ybp
CR-T12	bulk	pre/ff	930 ±60 ybp	AMS	792 – 916 cal ybp	729 – 954 cal ybp
CR-T15	bulk	pre/ff	1,060 ±70 ybp	AMS	923 – 1,058 cal ybp	796 – 1,170 cal ybp

* calibrated using Stuiver and Reimer (1993) and Reimer and others (2004).

Calibrated Dates that Relate to PE2

Sample #	Material	Pre/Post	Radiocarbon Date	Analysis	Calibrated Dates* 1-Sigma Range	Calibrated Dates* 2-Sigma Range
WC-2	bulk	post	2,370 ±40 ybp	AMS	2,342 – 2,458 cal ybp	2,331 – 2,682 cal ybp
DCP1-25a	char.	pre	1,770 ±60 ybp	AMS	1,608 – 1,810 cal ybp	1,543 – 1,857 cal ybp
DCP1-1a	char.[1]	post	1,780 ±60 ybp	AMS	1,619 – 1,811 cal ybp	1,553 – 1,862 cal ybp
DCP1-7C	char.	post?	2,070 ±60 ybp	AMS	1,951 – 2,120 cal ybp	1,886 – 2,298 cal ybp

* calibrated using Stuiver and Reimer (1993) and Reimer and others (2004).

1 = in-situ burn layer

Calibrated Dates that Relate to PE3

Sample #	Material	Pre/Post	Radiocarbon Date	Analysis	Calibrated Dates* 1-Sigma Range	Calibrated Dates* 2-Sigma Range
WC-1	bulk	post	7,720 ±50 ybp	AMS	8,444 – 8,546 cal ybp	8,417 – 8,589 cal ybp

* calibrated using Stuiver and Reimer (1993) and Reimer and others (2004).

Peavine Peak fault

Sample #	Material	Radiocarbon Date	Analysis	Calibrated Dates* 2-Sigma Range
RC-1	bulk	6,220 ±100 ybp	AMS	6,810 – 7,410 cal ybp
RC-3	bulk	5,540 ±100 ybp	AMS	6,020 – 6,600 cal ybp

* calibrated using Stuiver and Reimer (1993) and Reimer and others (2004).

Eglington fault

Sample #	Material	Location	Radiocarbon Date	Analysis	Calibrated Dates* 2-Sigma Range
UCLA-536	shell	unit D	22,600 ±550 ybp	conv.	too old (≈25 ky)
GS-2958	char.	graben	18,690 ±170 ybp	conv.	21,803 – 22,613 cal ybp
W-5649	carbon	post-D	14,040 ±320 ybp	conv.	15,871 – 17,877 cal ybp

* calibrated using Stuiver and Reimer (1993) and Reimer and others (2004).

Black Hills fault zone

Sample #	Material	Pre/Post	Radiocarbon Date	Analysis	Calibrated Dates* 2-Sigma Range
BHFFWVF-1	carbonate	pre-PE1	9,230 ±80 ybp	conv.	10,220 – 10,580 cal ybp
HWUC-1	carbonate	pre-PE1	10,870 ±70 ybp	conv.	12,650 – 13,130 cal ybp
FWUC-11-W	carbonate	pre-PE4	16,650 ±90 ybp	conv.	20,360 – 19,330 cal ybp
HWDW-1	carbonate	pre-PE4	19,290 ±120 ybp	conv.	23,540 – 22,260 cal ybp
HWLC-1	carbonate	pre-PE4	21,550 ±130 ybp	conv.	out of range (≈25? ky)

* calibrated using Stuiver and Reimer (1993) and Reimer and others (2004).

Pyramid Lake fault zone

Sample #	Material	Pre/Post	Radiocarbon Date	Analysis	Calibrated Dates* 2-Sigma Range
PLTF-B1	bone	post-PE1	880 ±35 ybp	AMS	710 – 910 cal ybp
PLTF-C2	det. char.	pre-PE1	1,790 ±80 ybp	AMS	1,530 – 1,880 cal ybp
GX-50054	org. sed.	post-PE4	7,555 ±250 ybp	conv.	7,870 – 9,000 cal ybp*
PLFT2-C1	det. char.	pre-PE4	8,060 ±45 ybp	AMS	8,720 – 9,240 cal ybp
GX-10055	org. sed.	pre-PE4	9,855 ±389 ybp	conv.	10,280 – 12,630 cal ybp*
NSRL-3014	bone	post-highstand	13,070 ±60 ybp	AMS	15,150 – 15,800 cal ybp*
ETH-12798	shell	pre-highstand	13,110 ±110 ybp	AMS	15,117 – 15,946 cal ybp*

* calibrated using Stuiver and Reimer (1993) and Reimer and others (2004).

Warm Springs Valley fault system

Sample #	Material	Pre/Post	Radiocarbon Date	Analysis	Calibrated Dates* 2-Sigma Range
GX31502	bulk	pre-PE2	9,970 ±550 ybp	conv.	9,950 – 12,942 cal ybp
GX30094	bulk	pre-highstand	11,980 ±90 ybp	AMS	13,663 – 14,039 cal ybp
GX30095	bulk	pre-highstand	15,550 ±110 ybp	AMS	18,677 – 18,986 cal ybp

* calibrated using Stuiver and Reimer (1993) and Reimer and others (2004).

Olinghouse fault zone

Sample #	Material	Pre/Post	Radiocarbon Date	Analysis	Calibrated Dates* 2-Sigma Range
Oling C-1	det. char.	pre-PE2?	3,170 ±90	AMS	3,080 – 3,640 cal ybp
Oling C-2	det. char.		2,880 ±190	AMS	2,490 – 3,470 cal ybp
Oling C-4	det char.		3,760 ±60	AMS	3,930 – 4,350 cal ybp
Tracy C-1	det. char.		1,990 ±35	AMS	1,865 – 2,005 cal ybp
Pat-soil 1	bulk		16,610 ±70	AMS	19,170 – 20,430 cal ybp
Pat-soil 2	bulk		10,880 ±50	AMS	12,650 – 13,130 cal ybp

* calibrated using Stuiver and Reimer (1993) and Reimer and others (2004).

Nevada Quaternary Fault Working Group **<u>Genoa fault</u>**
Fault Form
co-prepared by Alan Ramelli

Fault Name

Genoa fault, Carson Range fault system
U.S. Geological Survey Fault and Fold Database Fault #1285

Introduction

The Genoa fault poses the largest earthquake hazard to the Reno-Carson City urban corridor and is one of the most active faults in Nevada. It is a major range-bounding normal fault with evidence for multiple large, latest Holocene paleoearthquakes (surface offsets of >5 m). The two most recent events may both be parts of major earthquake sequences that ruptured the entire frontal fault system, with the most recent sequence occurring about 500 to 900 yr ago, and a prior sequence about 2000 to 2500 yr ago.

The prominent expression of the Genoa fault prompted early researchers to comment on its activity (Russell, 1887; Lawson, 1912). Fault mapping and scarp profile studies were conducted by Pease (1979a, 1979b, 1980). Paleoseismic studies including trenching were conducted by Ramelli and others (1994, 1999, and 1999a).

Tilting of the floor of Carson Valley deflects the Carson River to the west side of the valley (Slemmons, 1975; Peakall, 1999), and the fault controls the locations of several major hot springs. A quarry just south of the town of Genoa provides a rare 30-m high exposure of the fault plane formed on sheared granitic rocks, revealing vertical striations and corrugations consistent with nearly pure normal slip.

The Genoa fault is one of the highest risk faults in Nevada, threatening the State Capital, Carson City, communities in the Carson Valley (e.g., Genoa, Minden, Gardnerville), Lake Tahoe communities, the Reno-Sparks metropolitan area, communities within the Sierra Nevada (e.g., Truckee), and the heavily populated area west of Sacramento in the Great Valley of California. The Genoa fault is commonly used in local earthquake planning scenarios.

Location and Length

The Genoa fault generally forms the bedrock/alluvium contact along the eastern front of the southern Carson Range, on the west side of Carson Valley. The fault can be traced roughly continuously from Pleasant Valley (south of Markleeville, CA) northward to Spooner Summit, a distance of ~50 km. If it connects with the Kings Canyon fault in the Carson City area, its length is ~60 km, and extension to the south along faults within the Sierra Nevada could increase its length to >75 km. All lengths are measured end-to-end for consistency.

Major Fault and Paleoseismic References

Ramelli, A.R., dePolo, C.M., and Bell, J.W., 1994, Synthesis of data and exploratory trenching along the northern Sierra Nevada fault zone: Final Technical Report to the National Earthquake Hazards Reduction Program, 65 p.

Ramelli, A.R., Bell, J.W., dePolo, C.M., and Yount, J.C., 1999, Large-magnitude, late Holocene earthquakes on the Genoa fault, west-central Nevada and eastern California: Bulletin of the Seismological Society of America, v. 89, p. 1,458-1,472.

Ramelli, A.R., dePolo, C.M., and Bell, J.W., 1999a, Paleoseismic studies of the northern Sierra Nevada Frontal fault zone: Final Technical Report to the National Earthquake Hazards Reduction Program, 16 p.

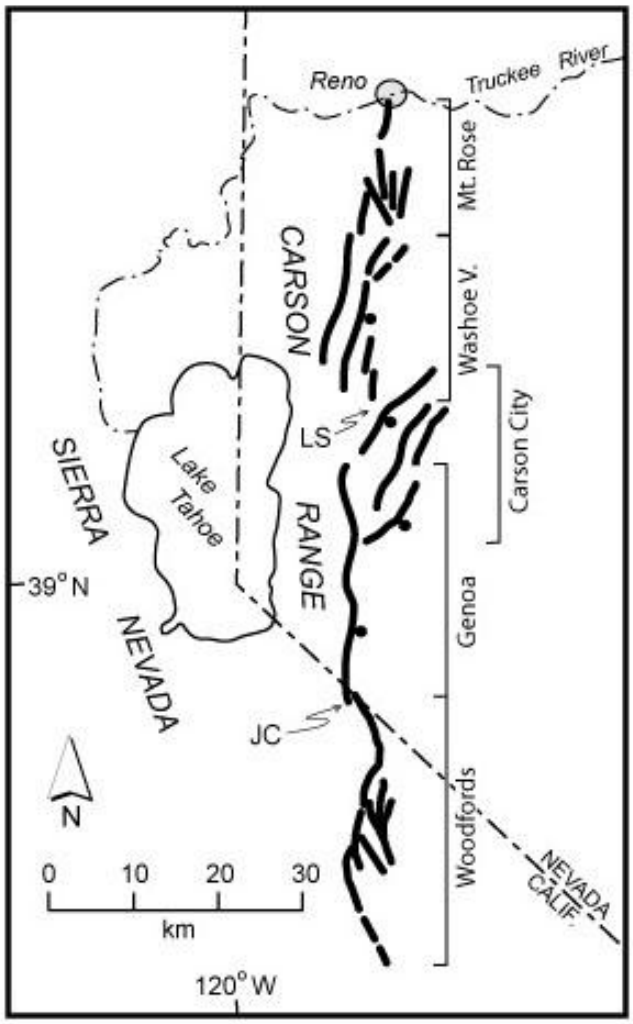
Geomorphic Expression

The Genoa fault forms one of the most prominent range fronts in the Basin and Range province. The fault generally forms an abrupt bedrock/alluvium contact, except at its ends where it splays into distributed patterns. The fault forms many geomorphic features indicative of its activity, including multiple-event scarps, nested graben, steepened hillside bases, large and small fault facets (as much as 350 m high), offset and uplifted alluvial terraces and talus slopes, and hot springs (Grover, Walleys, and Hobo Hot Springs).

Structural Description

The Genoa fault is part of the Carson Range fault system, the frontal fault system bounding the eastern side of the Carson Range. The system consists of a series of north-striking normal faults, and in general, becomes increasingly distributed to the north. Lawson (1912) first discussed dividing the Genoa fault into segments based on youthful fault scarps and geomorphic expression of the range front; this is one of the earliest discussions of segmenting a fault, possibly making Lawson the “Father of Segmentation”.

The Carson Range fault system can be divided into at least **two major earthquake segments** based on the character of faulting and a major discontinuity formed in the system where the Virginia Range impinges on the Carson Range, just north of Carson City. These two earthquake segments are generally referred to as the Genoa fault and the Mt. Rose fault zone. The system can further be divided into **five structural segments:** from south to north, the Woodfords, Genoa, Carson City, Washoe Valley, and Mt. Rose segments.



Major structural segments of the Carson Range fault system. The system is believed to typically rupture with two events: 1) the Genoa fault (Woodfords, Genoa, and Carson City segments); and 2) the Mt. Rose fault zone (Washoe Valley and Mt. Rose segments). LS - Lakeview Summit; JC - Jobs Canyon.

The southern half of the system, the Genoa fault, is structurally simple in its central part and has distributed ends. To the north, the Genoa fault splays into three principal, northeast-striking faults: the Indian Hill, Carson City, and Kings Canyon faults. The **Virginia Range transverse ridge** forms a bedrock high (i.e., Lakeview Summit) along the Carson Range front. South of Lakeview Summit, young scarps swing to the northeast and bound the southeastern side of the Virginia Range, while faults to the north decrease in displacement southward toward this area. Faults do extend through this bedrock high, but structural relief is about a third or less than in Carson Valley and young scarps are not obvious. The timing of the most recent events north and south of Lakeview Summit are close, and overlap in uncertainties allows a single rupture. However, age constraints have consistently indicated that rupture to the south (Genoa fault – 330 to 680 cal ybp) is more recent than to the north (Mt. Rose fault zone - 630 to 910 cal ybp). The Virginia Range transverse ridge is the largest structural disruption in the Carson Range fault system, and appears to be a major earthquake segment boundary.

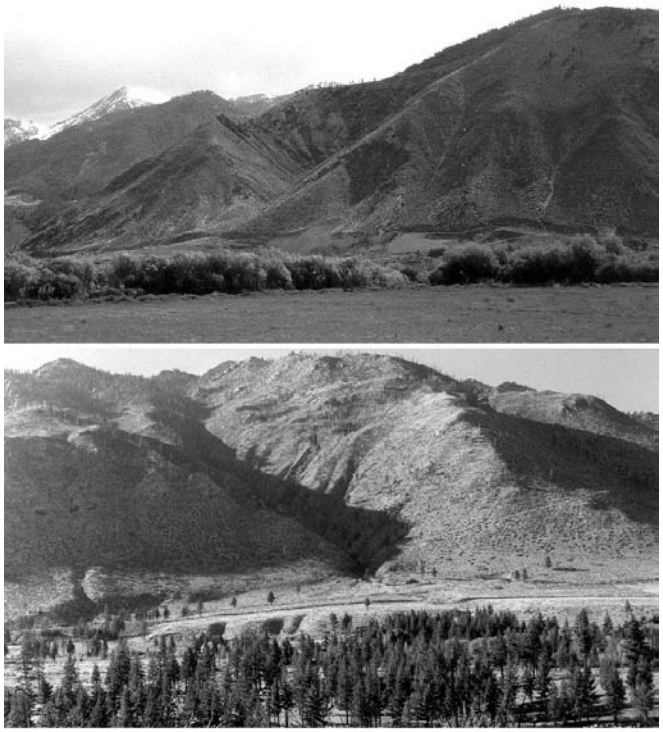
Ramelli and others (1994) divided the Genoa fault into three structural segments: south-to-north, the Woodfords, Genoa, and Carson City segments. The **Woodfords structural segment** is about 26 km in length and was further subdivided by Ramelli and others (1994) into two sections, the Diamond Valley and Sierran sections based on fault position and complexity. The Diamond Valley section has a single principal range front fault and some distributed faulting in the hanging wall, whereas along the Sierran section, the fault splays into two primary traces, Quaternary offsets decrease, faulting becomes more

distributed, and average elevation increases as the fault extends into a large ramp between major left-stepping faults in the Sierran front. Sawyer (2007 pers. comm.) has followed possible Quaternary activity along the fault as far south as the Mokelumne River, based on aerial observations of geomorphic features. A spectacular compound fault scarp occurs in glacial outwash deposits of the West Fork of the Carson River at the town of Woodfords (this is where Clark and others (1984) estimate a preferred slip rate of 1 m/ky over the last 10-13 ky). Ramelli and others (1994) measured a long profile across this scarp and estimated the vertical separation of the outwash surface to be 11.7 ±0.5 m. North of Woodfords, there is a basal range front fault, but the fault lacks the prominent expression that it has to the north.

Scarp in outwash terrace at Woodfords.

The Woodfords segment is separated from the Genoa segment by a 1.5 km left step in the fault at Jobs Canyon. Stewart and others (1982) map a bedrock fault along Jobs Canyon (an extension of the Waterhouse Peak fault in Hope Valley) that obliquely intersects the Genoa fault and likely influences the formation of this step. The most recent event is believed to have ruptured through this discontinuity, although displacements significantly diminish to the south: single-event displacements to the north are generally 4 to 5 m, whereas to the south they are 1 to 3 m (Ramelli and others, 1994).

The **Genoa structural segment** is the most spectacular part of the Carson Range fault system with a single basal normal fault, 1200 to 1500 m of topographic relief, and an estimated 800 m of basin fill (Maurer, 1985). The range front has many fault facets, and alluvial fans are relatively small due to being drowned by valley sediments. The Genoa segment is about 25 km long. Ramelli and others (1994) subdivided it into two sections, the Carson Valley and Jacks Valley sections. The 18-km long Carson Valley section is marked by a prominent scarp formed from the last two events and located at the bedrock/alluvium contact near the top of the small piedmont along the base of the range. The Jacks Valley section is north of where the Carson City and Indian Hill faults intersect the Genoa fault at a salient in the range front.



Comparison of fault scarp expression just south of Genoa (top) and just north of Woodfords (bottom)

This short, 7.5 km long, section has a more northwesterly strike (N16ºW) than the Genoa section (N4ºE). Despite its short length and significantly less downdrop of the hanging wall, the Jacks Valley section has the largest measured displacements along the Genoa fault (~5.5 m).

The Genoa and Carson City structural segments overlap by about 7 km, virtually all of the length of the Jacks Valley section.

The **Carson City structural segment** of the Genoa fault consists of a broadly distributed fault system (width up to 8 km) that includes three principal northeast-striking faults: the Indian Hill, Carson City, and Kings Canyon faults. The Kings Canyon fault is the longest of the three (~12.5 km long), lies online with the Genoa fault, and has a range front position. These faults are discussed in separate reports.

Earthquake Segmentation and Fault Length

The two most recent earthquakes along the Genoa fault were major events that may have ruptured the entire southern half of the Carson Range fault system (from south of Woodfords to north of Carson City). These two events ruptured most, if not all, of the Genoa fault, and may have involved all three northeast-striking faults in the Carson City area (Indian Hill, Carson City, and Kings Canyon faults). Much of the Genoa fault ruptured with displacements of >4 m, with the largest measured displacement (~5.5 m) occurring in Jacks Valley.

An absolute minimum earthquake segment length (~25 km) is the central part of the Genoa fault, where scarps can be traced nearly continuously from the Jobs Canyon discontinuity to the north end of Jacks Valley. There are structural discontinuities along this section, including two range salients, but the continuity of fault scarps indicate that the two most recent events ruptured through them.

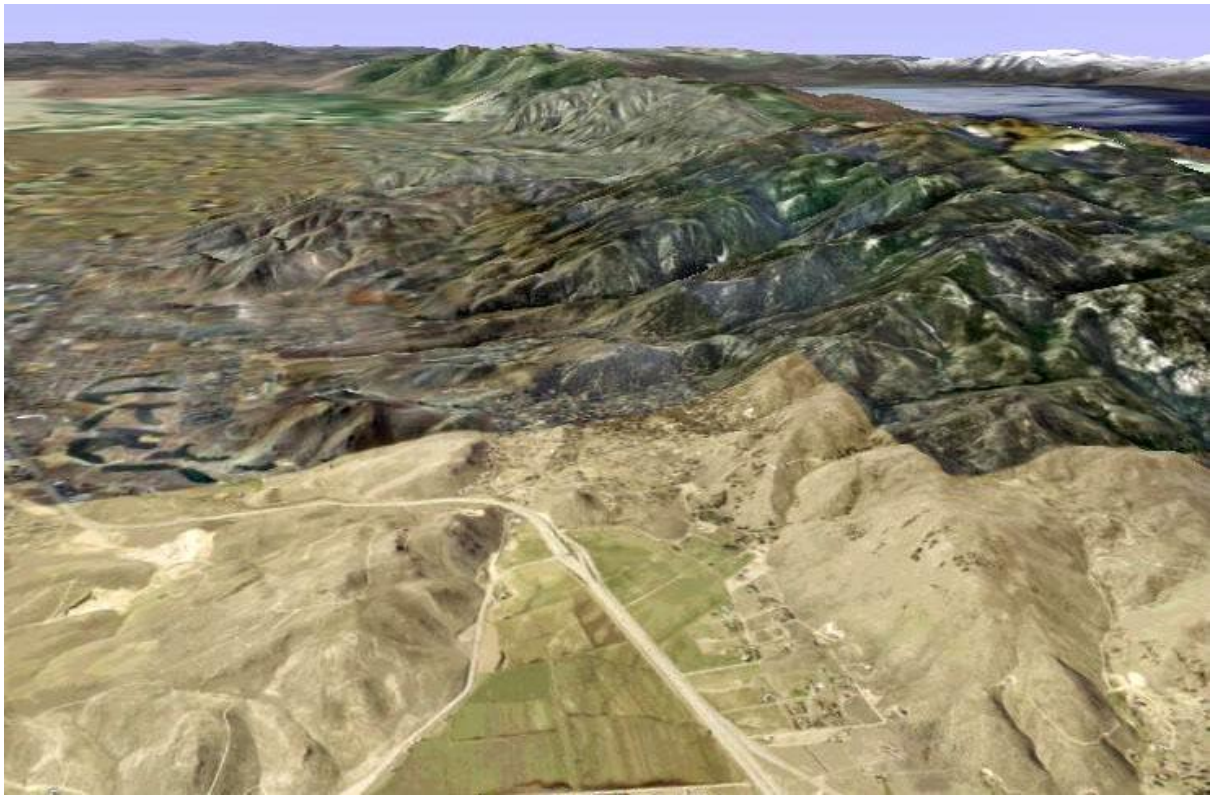
A preferred minimum length (~33 km) assumes that scarps along the range front south of Jobs Canyon and in the outwash terrace at Woodfords were formed during the most recent event on the central Genoa fault, but there currently is no direct evidence to either confirm or refute this interpretation. The Jobs Canyon discontinuity is a 1½-km left step in the trace of the fault, across which fault scarp heights diminish to the south. With normal displacement, slip can be conserved across this step with no major volume change. We assume that most large earthquakes rupture through this discontinuity, but some absorption of momentum or differential potential occurred across this step because displacements appear to change across it.

The preferred length of 62 km includes the entire length of the Genoa fault having range-front morphology and the northeast-striking fault splays near Carson City. Such a length would be more consistent with the large surface displacements created by the two most recent events. The strongest evidence for coincident rupture of these northern splays comes from the Carson City fault, where a single trench revealed two recent events with

the same general ages as those along the Genoa fault. The most recent event from the Carson City fault is dated by a piece of detrital charcoal taken from the lower part of a fissure formed during that earthquake. Due to the position of the sample, this age (316 - 513 cal ybp) is considered to closely approximate the age of the most recent event. An upper limit on the age of the penultimate event is based on an age from the faulted alluvium (2,348 – 2,953 cal ybp); the penultimate event occurred after deposition of the alluvium, so rupture coincident with the Genoa fault is permissible, albeit loosely constrained. Pease (1979a, 1979b) and Bell and Pease (1980) identified two Holocene events in a trench across the Indian Hill fault, but did not have any direct age control to constrain the events. A young scarp of similar freshness as the Genoa fault is present along the south side of Indian Hill and projects through this trench site. The Kings Canyon fault also has no direct age control constraining recent events, but Trexler and Bell (1979) identified evidence for at least three post-Tioga events, including a small scarplet in loose, grusy materials that they interpreted to be only a few hundred years old. Of the three faults, the Kings Canyon is the most structurally in-line with the Genoa fault and has a similar range-front character

Considering the possibility of rupture to the south along faults within the Sierra Nevada, the length of the Genoa fault would be 67 km (from near Mokelumne River, in the south, to northern Jacks Valley), or 78 km if the Kings Canyon fault is included.

Earthquakes rupturing the entire Carson Range fault system, including the Mt. Rose fault zone, cannot be entirely ruled out, but available age constraints indicate that the northern part of the system ruptured somewhat earlier than the southern part (see Mt. Rose fault zone report). Further, such events (rupture lengths of ~100 km) would be unusual for normal faults. Rupture of the entire system during a single event is considered very unlikely.



Google Earth image looking south at Lakeview summit (foreground).
Genoa fault and Lake Tahoe in the background.

Earthquake History

Ramelli and others (1999) used three trenches to constrain the age of the two most recent events along the Genoa fault: Paleoearthquakes 1 and 2. As many as four earthquakes offset a Tioga outwash plain (~15 ka) near the town of Woodfords, CA (Ramelli and others, 1994, 1999).

Paleoearthquake Summary for the Genoa Fault

PE1	preferred range	520-660 cal ybp
	two-sigma range	330-680 (910)[1] cal ybp
PE2	preferred range	1,930-2,460 cal ybp
	two-sigma range	1,740-2,700 cal ybp
PE3	preferred	Holocene
PE4?	preferred	Holocene?

1 – The 680 ybp age is the preferred maximum, but some uncertainty exists whether this layer is actually faulted. The youngest clearly faulted layer yielded an age of 910 ybp, but this must be somewhat older than PE1 because subsequent deposition occurred prior to the event.

Paleoearthquake 1 (most recent event)

Evidence for a recent earthquake along the Genoa fault was recognized by Russell (1887). Lawson (1912) asked early settlers if the scarp formed historically, but they stated that the scarp was unchanged since their arrival in the mid-1800s. These were the first fault scarp morphology observations in Nevada. Based on soils and scarp morphology, Pease (1979a, 1979b, 1980) suggested the most recent event occurred within the past several hundred years. Ramelli and others (1994, 1999) constrained Paleoearthquake 1 (PE1) with radiocarbon dating, principally from preserved forest fire deposits; evidence for each trench is discussed below.

Jacks Valley site:

The Jacks Valley trench was excavated into a 6-m scarp in a late Holocene fan. The trench exposed sandy deposits with at least 15 layers containing disseminated charcoal, interpreted to be related to forest fires. Twelve faults were exposed in a zone over 12 m wide. All deposits except the upper sandy colluvium in the trench are faulted by PE1. The average orientation of the principal fault traces in the trench is N10ºE, 65º E. The summed brittle offset across all the fault traces during PE1 is 3.2 ±0.5 m (Ramelli and others, 1999).

The oldest post-PE1 age (580 ±110 ybp) comes from unfaulted sandy colluvium. Faulted deposits yielded uncorrected radiocarbon ages ranging from 2,100 to 525 ybp (Ramelli

and others, 1999). The youngest pre-PE1 age (525 ±120 ybp) comes from the uppermost layer interpreted to be offset; this is still our preferred interpretation, but there is some uncertainty in whether the layer is actually faulted. A clearly faulted deposit was dated at 755 ±100 ybp.

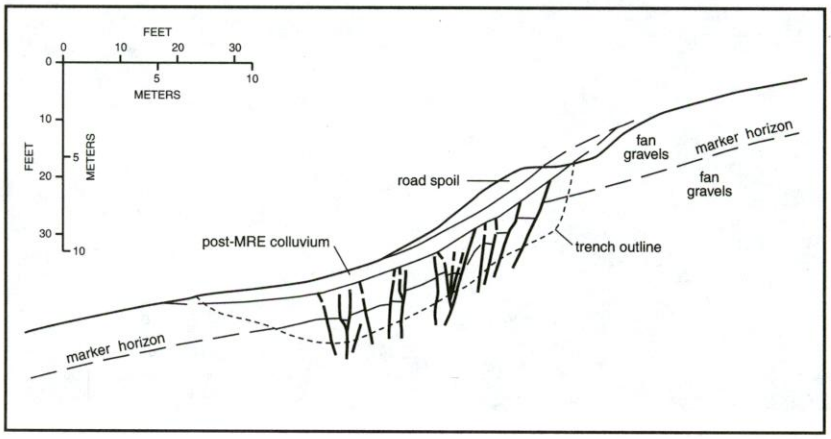


Figure 6. Simplified cross section at the Jacks Valley trench site based on trench relations and an adjacent surveyed topographic profile. Consistent stratigraphic position of a marker horizon (strongest charcoal layer) indicates that the trench exposed alluvial fan deposits displaced by more than 5 m during the most recent event.

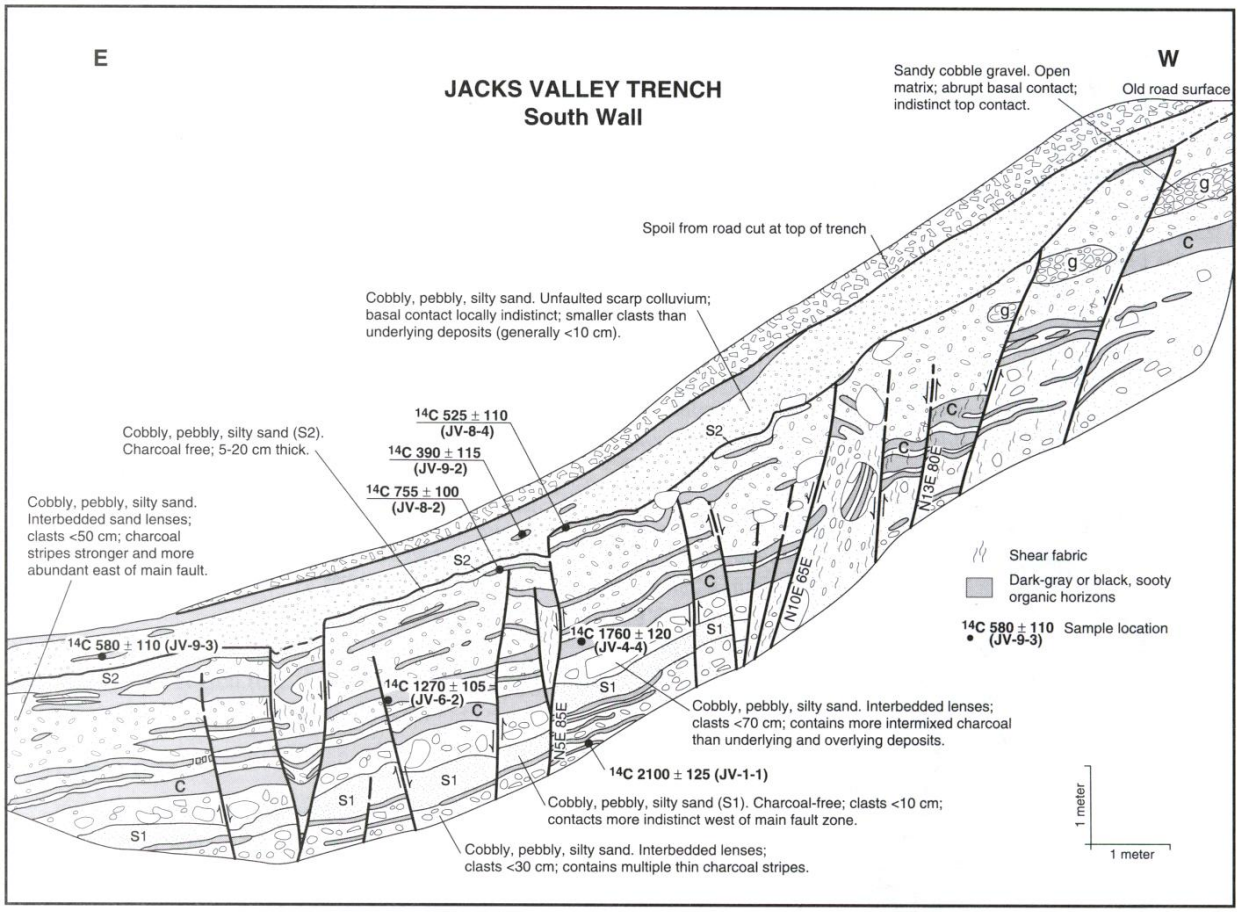


Figure 5. Log of the Jacks Valley trench, located at the mouth of an unnamed drainage on the west side of Jacks Valley. Deposits are generally indistinguishable, but a gravel lens (g), two sand lenses (S1 and S2), and the strongest of several charcoal layers (C) serve as marker horizons. Deposits ranging in age from about 600 to 2000 cal B.P. are offset by consistent amounts, indicating the most recent event (estimated to have occurred between 500 and 600 cal B.P.) caused displacement of more than 5 m at this site.

Walleys site:

The Walleys trench was excavated into a 10-m scarp at the head of an alluvial fan near Walleys Hot Springs (Ramelli and others, 1999). The trench exposed offset fan deposits and buttressed and faulted scarp colluvium. Due to the height of the fault scarp, steepness of the slope, and coarse nature of the fan deposits, cobbles and boulders tended to collect at the base of the scarp in a debris pile (the distal facies), whereas the proximal facies is a series of gravelly wash slope deposits, probably caused by overflow of the adjacent ephemeral stream. The orientation of the bedrock fault plane in the trench is N15ºE, 58º E.

Trench and surface offset measurements indicate that two events caused 8.2 ±0.6 m normal dip slip at this site (Ramelli and others, 1999). Trench reconstruction suggests the most recent event (PE1) had a slightly larger displacement (~4.5 m) than PE2 (~3.7 m). Two radiocarbon samples from the Walleys trench yielded anomalous ages and are disregarded.

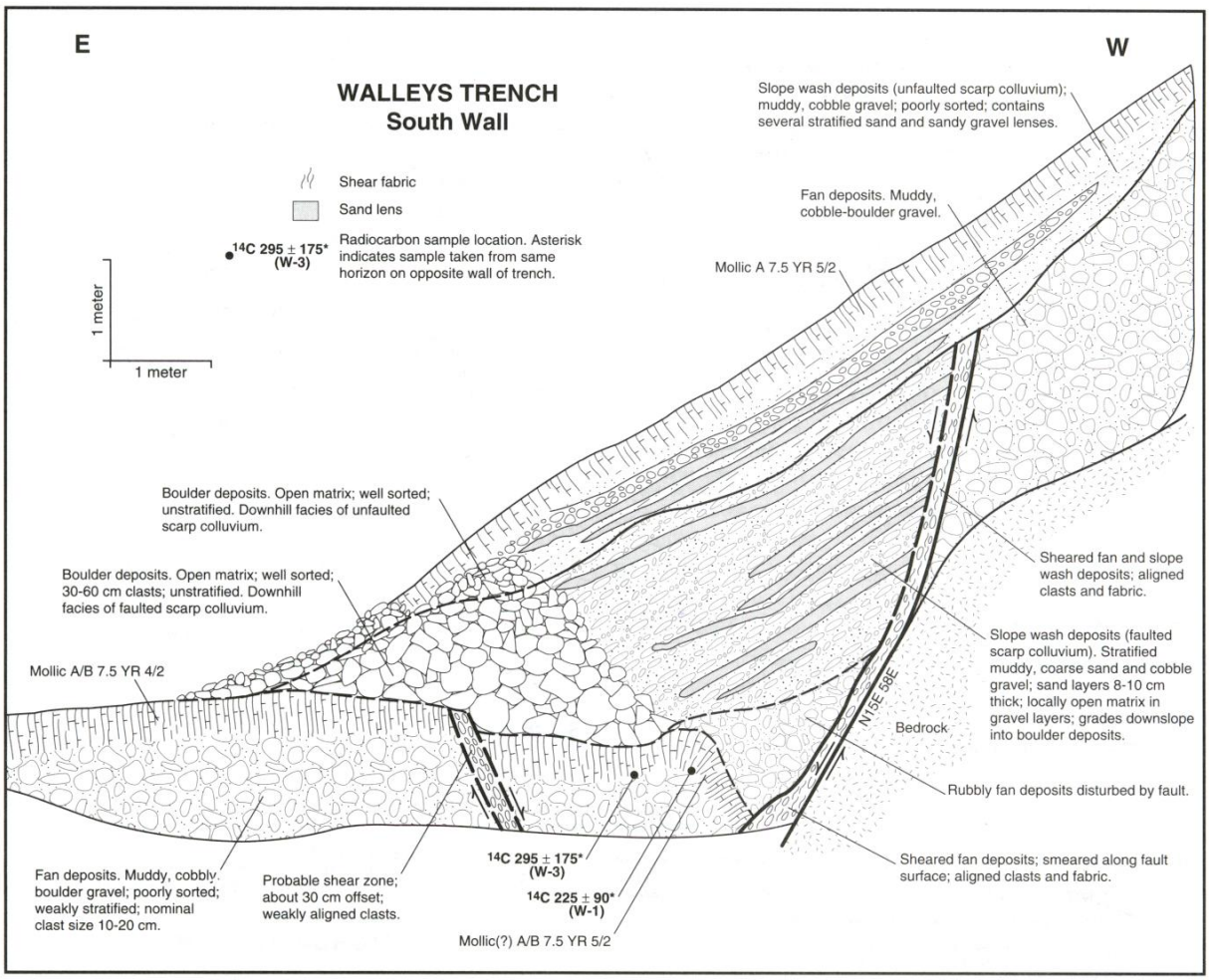


Figure 8. Log of the Walleys trench, located on the lower and smaller of two uplifted terraces near Walleys Hot Springs (Fig. 7). The trench exposed fan deposits displaced by more than 8 m during two events. Two charcoal samples yielded anomalous modern ages and are thus disregarded.

Sturgis site:

The Sturgis trench, excavated into a 6-m scarp at the mouth of Corsser Creek, exposed a lower section of faulted deposits that can be divided into two packages, a lower coarse sand (grus) and an upper fine sand containing several layers of disseminated charcoal. The fine sand is disconformably overlain by scarp colluvium (Ramelli and others, 1999). Two principal faults strike ~N30ºE and dip 55º to 70º E. The downthrown section of alluvium is thicker, and in part older, than the footwall deposits indicating it draped and buried a pre-existing fault scarp (Ramelli and others. 1999). The trench revealed clear evidence of two events; an eastern fault trace is truncated by deposits that are in turn faulted by a western (main) trace that slipped during both events. Unfaulted colluvium was dated at 580 ±115 ybp, and footwall deposits interpreted as faulted only by PE1 at 1,370 ±120 ybp. A date of 1,025 ±315 ybp from unfaulted colluvium has a larger than average error, and may be reworked, so it is disregarded.

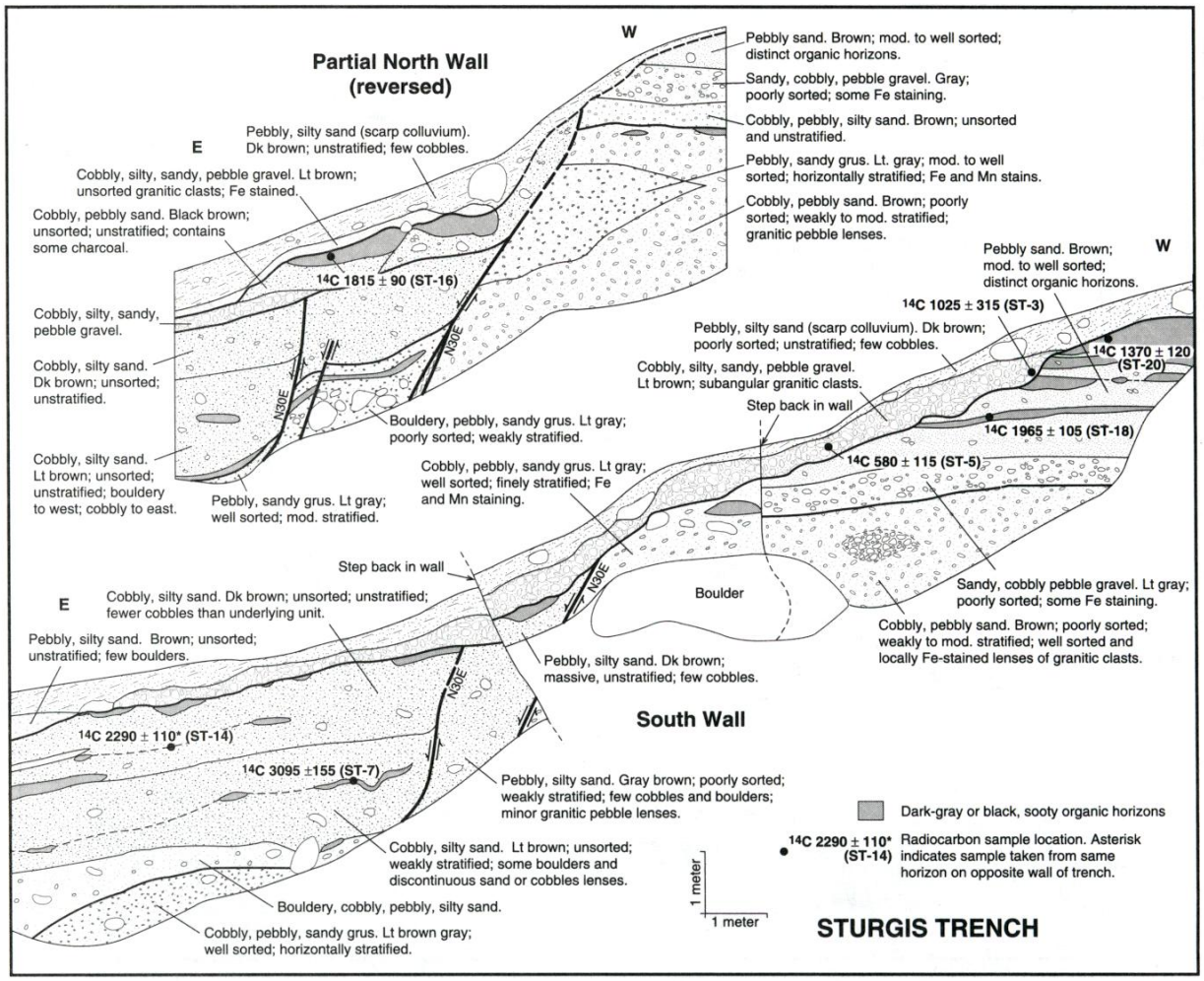


Figure 9. Log of the Sturgis trench, located at the mouth of Corsser Creek. The trench exposed fan deposits displaced by about 6 m during two events. The fan deposits are separated into two units (an upper group of dominantly fine sand deposits and a lower group of dominantly coarse sand or grus deposits); the boundary between the two units is denoted by the lowermost bold contact. The upper bold contacts denote disconformities buried by scarp colluvium and gravel deposits that flowed over and draped the scarp.

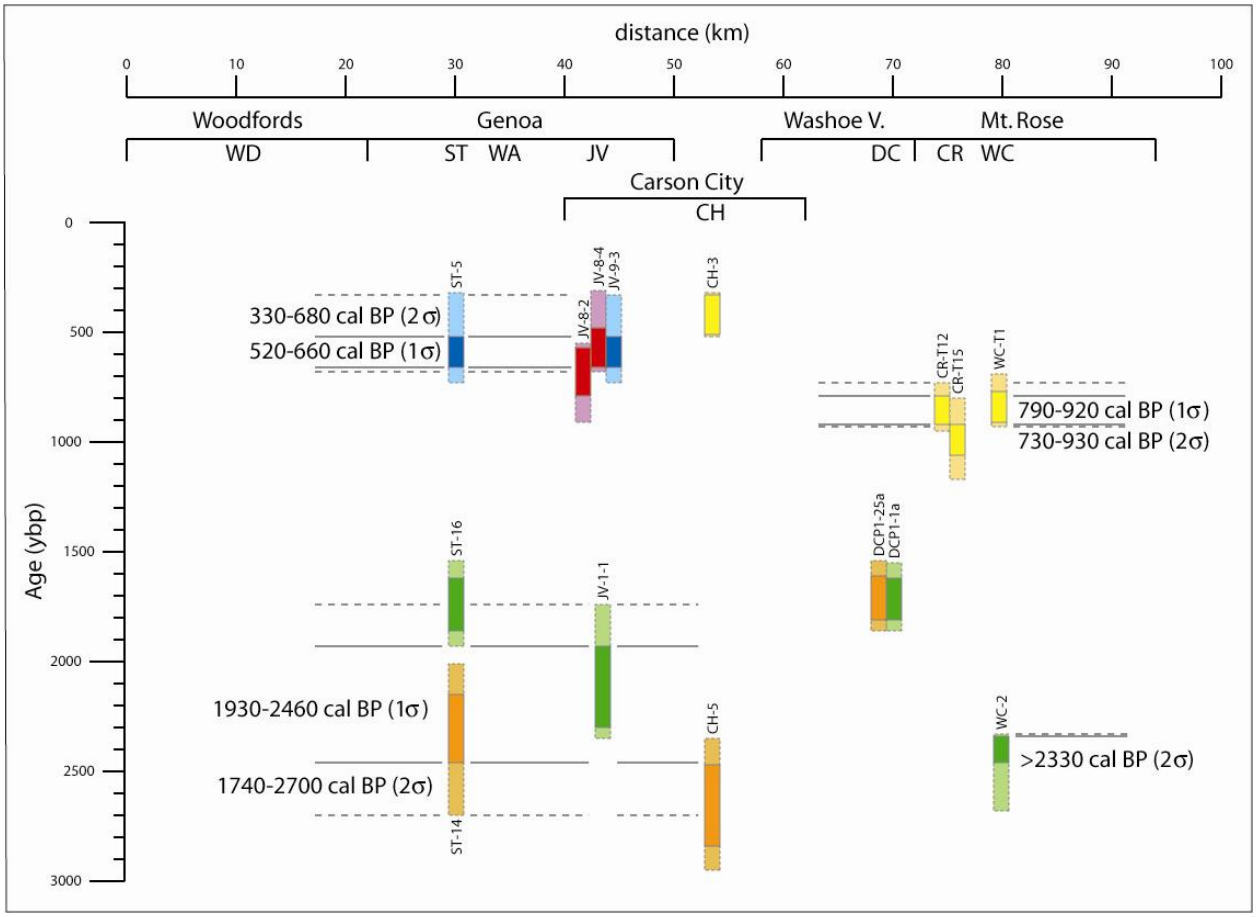
PE1 Summary:

Ramelli and others (1999) rounded calibrated years off to the nearest decade, and we have done likewise below. Based on updated calibration curves, our preferred age range for PE1 is now 520-660 cal ybp, and the two-sigma range is 330-680 cal ybp.

Table of Calibrated Dates that Relate to PE1

			Calendar Corrected Dates*	
Sample	Pre/Post PE1	Radiocarbon date	1-sigma range	2-sigma range
JV-9-3	Post	580 ±110 ybp	523 – 657 ybp	326 – 732 ybp
JV-8-4	Pre	525 ±120 ybp	476 – 660 ybp	308 – 683 ybp
JV-8-2	Pre	755 ±100 ybp	565 – 787 ybp	548 – 907 ybp
ST-5	Post	580 ±115 ybp	519 – 660 ybp	320 – 734 ybp

JV = Jacks Valley site; ST = Sturgis site
* Stuiver and Reimer (1993) and Reimer and others (2004)



Constraining ages for recent events along the Carson Range fault system.

If the interpretation that JV-8-4 predates PE1 is incorrect, the upper constraint is somewhat looser, with the youngest clearly faulted deposit (JV-8-2) constraining PE1 to post-790 cal ybp (or post-910 cal ybp, 2-sigma). Some deposition separates sample JV-8-2 from the event horizon; extrapolating the average sedimentation rate suggests that PE1 post-dates JV-8-2 by approximately 80 to 100 years, but deposition is likely episodic.

Ramelli and others (1999) considered a mean residence time (MRT) factor of 50 – 100 years for estimating minimum ages, assuming the charcoal layers are a mixture of material spanning a few to several decades. However, it is uncertain whether a mean residence time should be applied in this case; charcoal from forest fires may be accumulated rapidly with little residence time, especially if preserved by subsequent deposition. For this discussion, we do not consider an MRT correction.

Historically the fault has not moved, so we can be confident that it is at least 150 years old (pre-1850). The fault scarp was apparently degraded at that time, indicating it was already at least 50 to 100 years old. Thus, a minimum PE1 age estimate of 200 to 250 years can be made using this logic.

Paleoearthquake 2

Jacks Valley site:

No direct evidence for Paleoearthquake 2 was found at the Jacks Valley site. We assume that PE2 ruptured the Jacks Valley section, similar to PE1. If so, then sample JV-1-1provides a minimum constraining date (1930 cal ybp; 1 sigma). If PE2 bypassed the Jacks Valley section, however (for example, ruptured the Carson City fault), it could have occurred somewhat later than this date (Ramelli and others, 1999).

Walleys site:

The Walleys trench revealed clear evidence of PE2 (i.e., scarp colluvium faulted by PE1), but did not yield any datable material to constrain PE2's age.

Sturgis site:

The age of PE2 is bracketed at the Sturgis trench between the uncorrected radiocarbon dates of 2,290 ± 110 ybp from a faulted colluvial deposit and 1,815 ± 90 ybp from an organic-rich part of overlying deposits faulted only by PE1. An alternative hypothesis for PE2 at the Sturgis site is that these dates are inherited detrital charcoal and that PE2 is actually younger than the youngest dated organic-rich deposit in the scarp deposits, 1,370 ± 120 ybp.

PE2 Summary:

Ramelli and others (1999) rounded calibrated years off to the nearest decade (as we have done here), and assumed a mean residence time factor of 50 – 100 years for estimating minimum ages because the charcoal layers are assumed to be a mixture of material spanning a few to several decades. As previously discussed, we do not include a mean residence time adjustment here.

PE2 is bracketed between 1,930 and 2,460 cal ybp (1-sigma), or 1,740 and 2,700 cal ybp (2-sigma). The older date was derived from a deposit about 50 cm below the uppermost horizon cut by PE2, so the event must be somewhat younger than this. If the event is younger than the uppermost date from the scarp deposits in Sturgis trench, then it is younger than 1,006 to 1,527 cal ybp.

Whereas the most recent event clearly ruptured the Jacks Valley section, we currently cannot preclude that some events, including the penultimate event, ruptured northward along the Indian Hill and/or Carson City faults, bypassing the Jacks Valley section. If the penultimate event ruptured the Jacks Valley section, then it occurred prior to 1,930 cal ybp (JV-1-1).

Table of Calibrated Dates that Relate to PE2

			Calendar Corrected Dates*	
Trench	Pre/Post PE1	Radiocarbon date	1-sigma range	2-sigma range
JV-1-1	Post-event(?)	2,100 ±125 ybp	1,930 – 2,302 ybp	1,742 – 2,352 ybp
ST-16	Post-event	1,815 ±90 ybp	1,624 – 1,865 ybp	1,535 – 1,933 ybp
ST-14	Pre-event	2,290 ±110 ybp	2,146 – 2,460 ybp	2,009 – 2,703 ybp
ST-20	Pre-event(?)	1,370 ±120 ybp	1,149 – 1,405 ybp	1,006 – 1,527 ybp

JV = Jacks Valley site; ST = Sturgis site
* Stuiver and Reimer (1993) and Reimer and others (2004)

Earthquake Recurrence Intervals

There are only two dated events on the Genoa fault, so there is limited direct evidence with which to estimate earthquake recurrence intervals. The interseismic interval that is available (PE2-PE1) is relatively short and will likely serve as a lower constraint.

The PE1 two-sigma range in time 330 to 680 ybp and the two-sigma range in time for PE2 is 1,740 to 2,700 ybp. This gives a range in possible interseismic intervals for PE2-PE1 of 1,060 to 2,370 years.

A latest Pleistocene average recurrence interval can be calculated using the offset Tioga outwash at Woodfords. The age of the abandonment of the Tioga outwash terrace by stream activity is suggested by Clark and others (1984) to be 10 to 13 ky ago. The lower

boundary, Holocene, can is calendar corrected to about 11,500 years as a minimum age for the abandonment. As a maximum age, the pluvial maximum of ~15.5 ka can be considered, assuming the outwash surface must have been active during this time. Calendar corrected dates from Adams and Wesnousky (1998) gives an age range for the highstand of Lake Lahontan to be 15,117 to 15,798 cal. ybp; thus, a maximum of 15,800 ybp is estimated for the abandonment. Ramelli and others (1984) estimate that three to four events created the fault scarp at Woodfords, including PE1. PE1 occurred 330 to 680 years ago, a time period that has to be removed to isolate the interseimic intervals. PE3 or PE4 are assumed to have occurred near the time of fluvial abandonment (11,500 to 15,800 ybp). Based on these assumptions there have been 2 or 3 interseismic intervals over 10,820 to 15,470 years (11,500 – 680 = 10,820; 15,800 – 330 = 15,470). The range of possible average interseismic intervals using the information from the Woodfords scarp is 3,606 to 7,735 years.

The range of earthquake recurrence for the Genoa fault is estimated to be between 1,060 to 7,735 years.

The Genoa fault likely has earthquakes that are clustered in time, as evidenced by the two relatively recent events. The probability that the next major earthquake on the Genoa fault will be part of this cluster should bear on the likelihood that the shorter part of the earthquake recurrence interval range is more representative.

Fault Slip Rates

"A slip rate of 2-3 mm/yr, derived from the average per-event displacement determined from trenching (4-5 m) and the interseismic interval between the two events (1.5-2 kyr), is considered a better estimate of late Holocene activity. At Woodfords, where displacements appear to be smaller and events possibly less frequent, the slip rate is about 1 mm/yr (Clark et al., 1984; this study)." (Ramelli and others, 1999)

Clark and others (1984) interpreted the offset surface at Woodfords to be late Tioga age, estimated to be 10 – 13 ky old. They estimated the displacement of this surface to be between 9 and 16 m. Clark and others (1984) report a preferred average Holocene slip rate of 1 m/ky and a range of 0.7 – 1.6 m/ky.

"We do not know how representative the Holocene slip rate, based on only a few events, is of the longer-term Quaternary slip rate. The few available constraints on longer-term activity suggest rates similar to, or less than, the Holocene rate. The outwash terrace of probable Tahoe age at Woodfords suggests an average slip rate of between 0.3 and 0.8 mm/yr, somewhat less than the Holocene rate at the same location." (Ramelli and others, 1999)

A long-term vertical rate was also estimated by Ramelli and others (1999). They note that,

"The vertical relief between this erosion surface [on top of the Carson Range ~ 2700 m elevation] and the floor of Carson Valley (about 1200 m), combined with the depth of fill in Carson Valley (550 – 1000 m; Maurer, 1985), suggests 1700 – 2200 m cumulative throw. Averaging this uplift over the current seismotectonic regime (i.e., 3 – 5 Ma; Huber 1981; Unruh, 1991) yields a long-term uplift rate of 0.3 – 0.7 mm/yr."

The best determined slip rate of the Genoa fault is at Woodfords, where the rate is about 1 m/kyr for approximately Holocene. To gain a perspective on what the Holocene rate near the central part of the Genoa fault is, a surrogate of relative single-event displacement can be considered (displacement is a factor of slip rate). The single-event displacement near the central part of the fault is about twice the displacement at Woodfords (4-5.5 m versus 2-3 m), thus we would expect that the slip rate of the central part of the Genoa fault to be about twice the slip rate at Woodfords, or about 2 m/ky.

The range of fault slip rates estimated for the Genoa fault is 0.3 to 2 m/ky.

Summary of Single-Event Displacements

"The two late Holocene earthquakes produced large displacements (3- to 5.5-m dip-slip per event) along more that 15 km of the Genoa fault. Offsets at the three trench sites suggest a general southward decrease in displacement during the most recent event, with about 5.5-m dip slip at the Jacks Valley site, about 4.5 m at the Walleys site, and about 3 m at the Sturgis site."
(Ramelli and others, 1999)

Photographs in this report were taken by Alan Ramelli and the radiocarbon table was created by Alan Ramelli.

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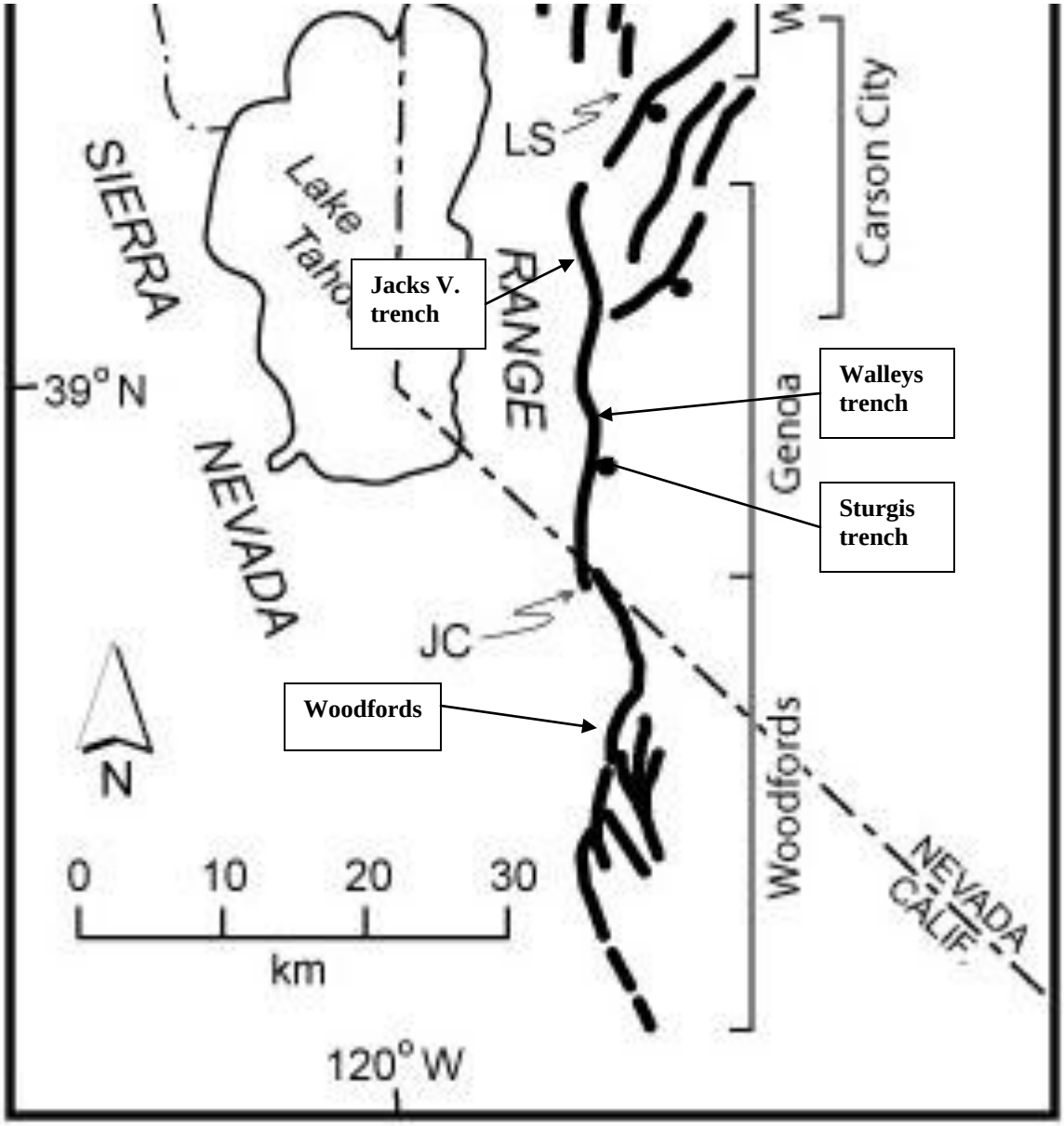
Location of trenches and Woodfords along the GENOA FAULT

Trench sites and the Woodfords site were not indicated in the Genoa report. The following are these locations. Please add this to the Genoa report.

The first figure is a labeled schematic map of the Genoa fault. The second and third are from Ramelli and others (1994) and are the trench sites and the Woodfords site, respectively.



Major structural segments of the Carson Range fault system. The system is believed to typically rupture with two events: 1) the Genoa fault (Woodfords, Genoa, and Carson City segments); and 2) the Mt. Rose fault zone (Washoe Valley and Mt. Rose segments). LS - Lakeview Summit; JC - Jobs Canyon.

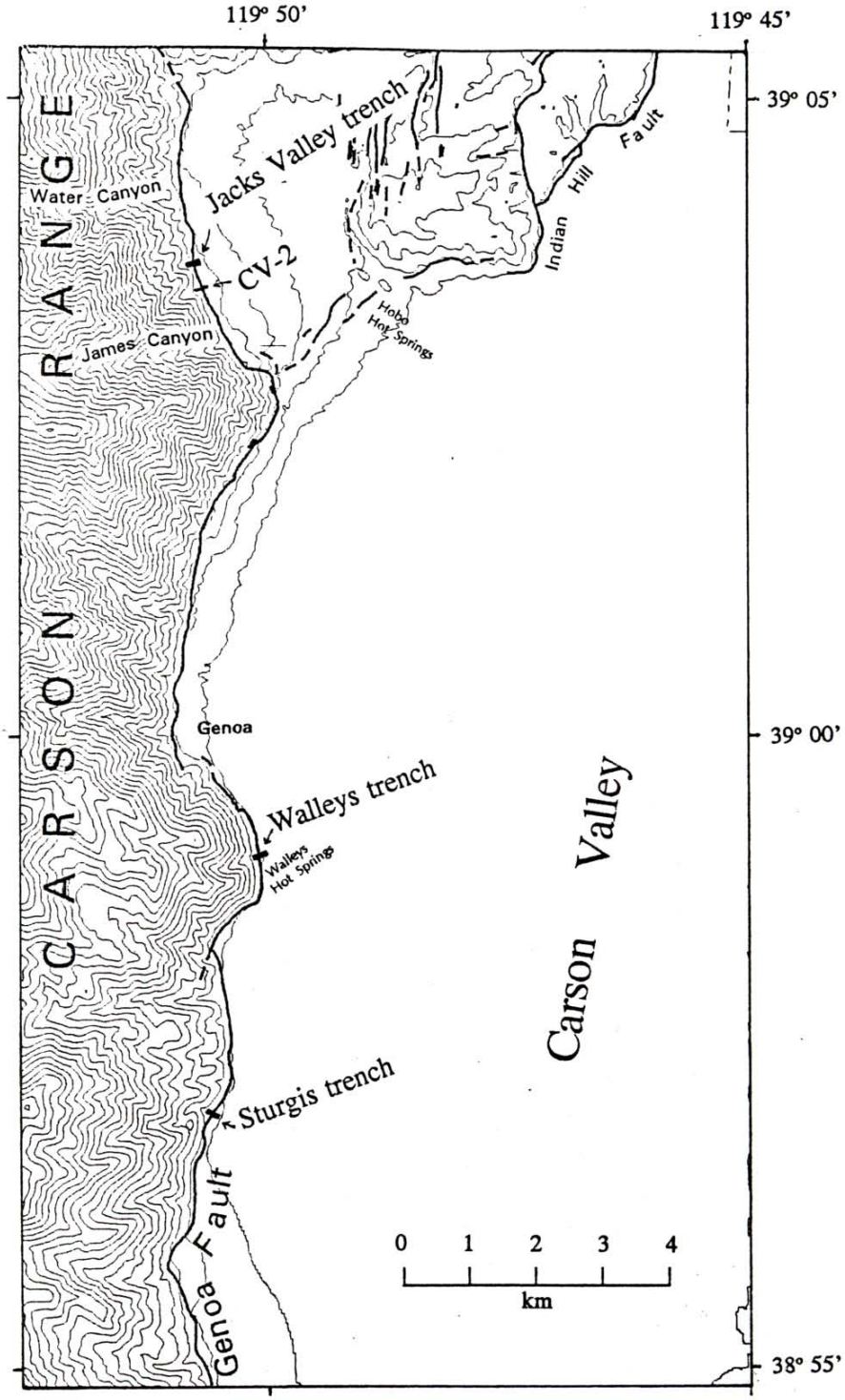


Figure 3: Locations of exploratory trenches (Jacks Valley, Walleys, and Sturgis trenches), excavated along the Genoa fault during mid-1992. Profiles Walleys 2 (fig. 9) and Walleys 3 (fig. 8) are located 50 m and 150 m south of Walleys trench, respectively, and profile Sturgis 2 (fig. 11) is located 50 m north of Sturgis trench. Contour interval 50 m.

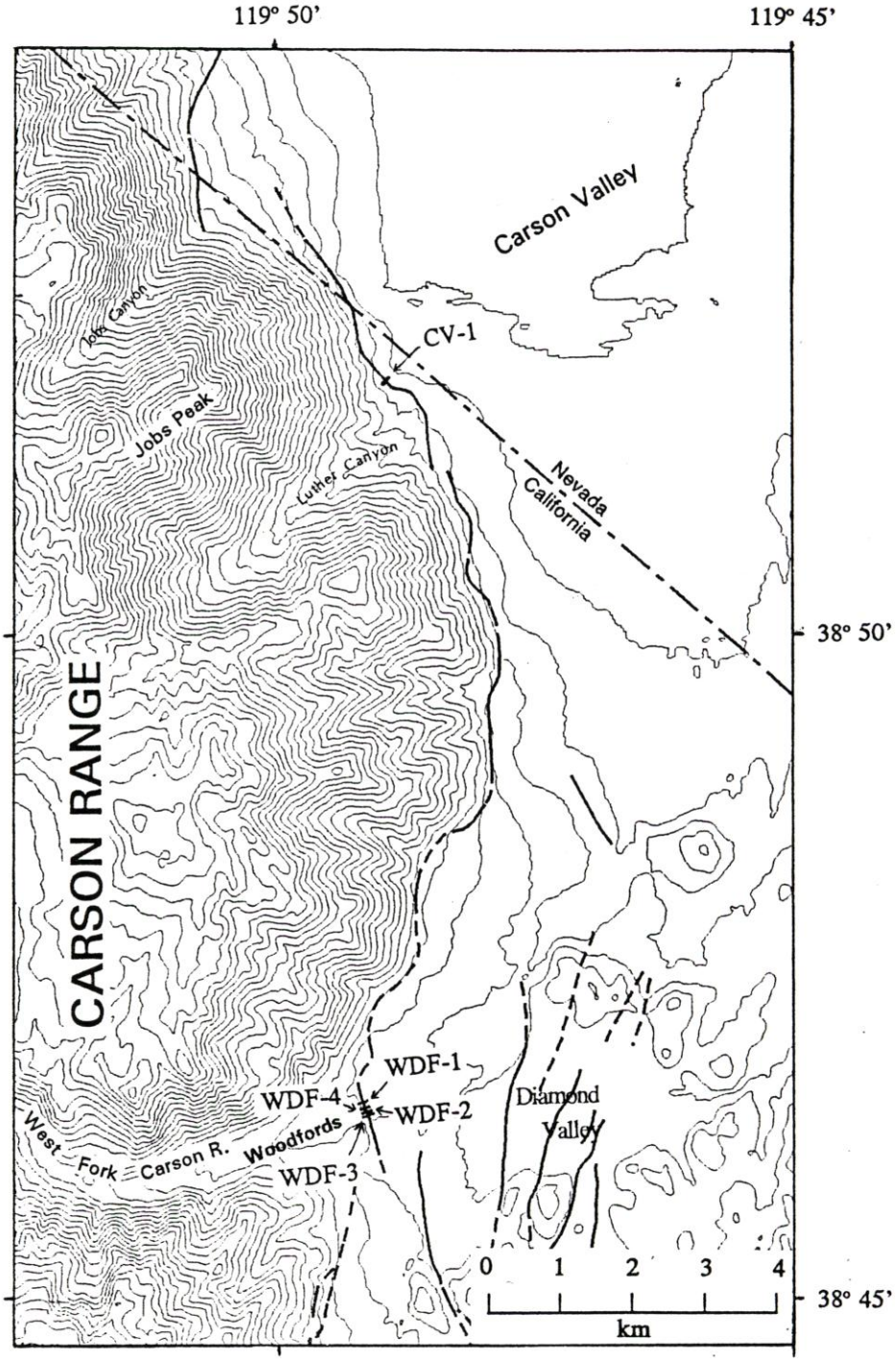
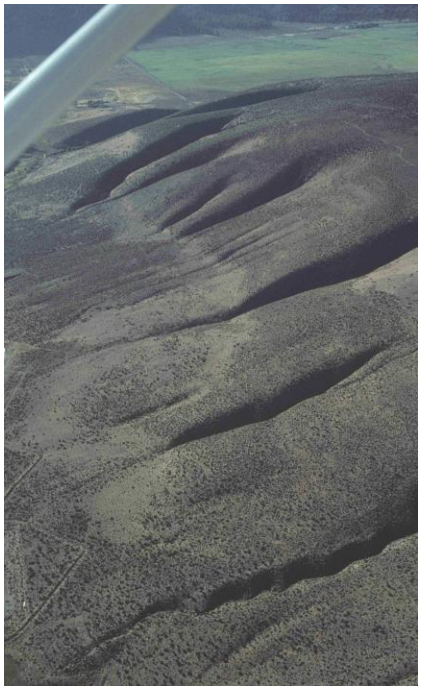


Figure 12: Locations of topographic profiles of fault scarps at Woodfords (WDF-1 to WDF-4; figs. 13-16) and near Luther Canyon (CV-1; fig. 17). Contour interval 50 m.

Nevada Quaternary Fault Working Group **<u>Indian Hill fault zone</u>**
FAULT FORM



Fault Name

Indian Hill fault zone
USGS Fault and Fold Database Fault #1652

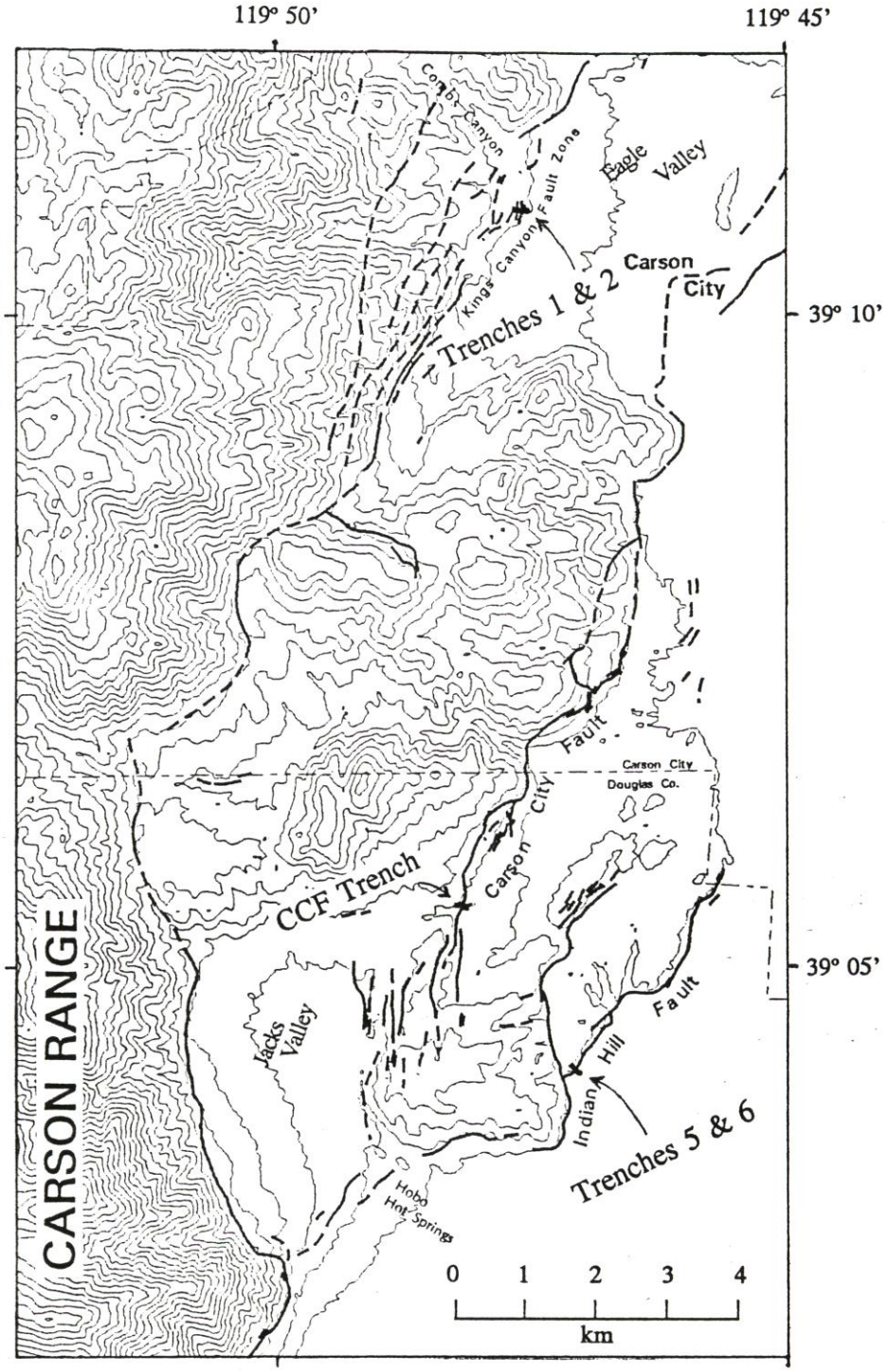
Introduction

The Indian Hill fault is one of three faults that the Genoa fault splits into at its north end. It is the easternmost fault and generally lies southeast of Carson City and a Native American colony named Stewart. Urban growth is rapidly developing around the Indian Hill fault zone, and several consultants trenches have been dug defining the fault zone. Part of the zone is used as a golf course, which is an excellent urban planning action.

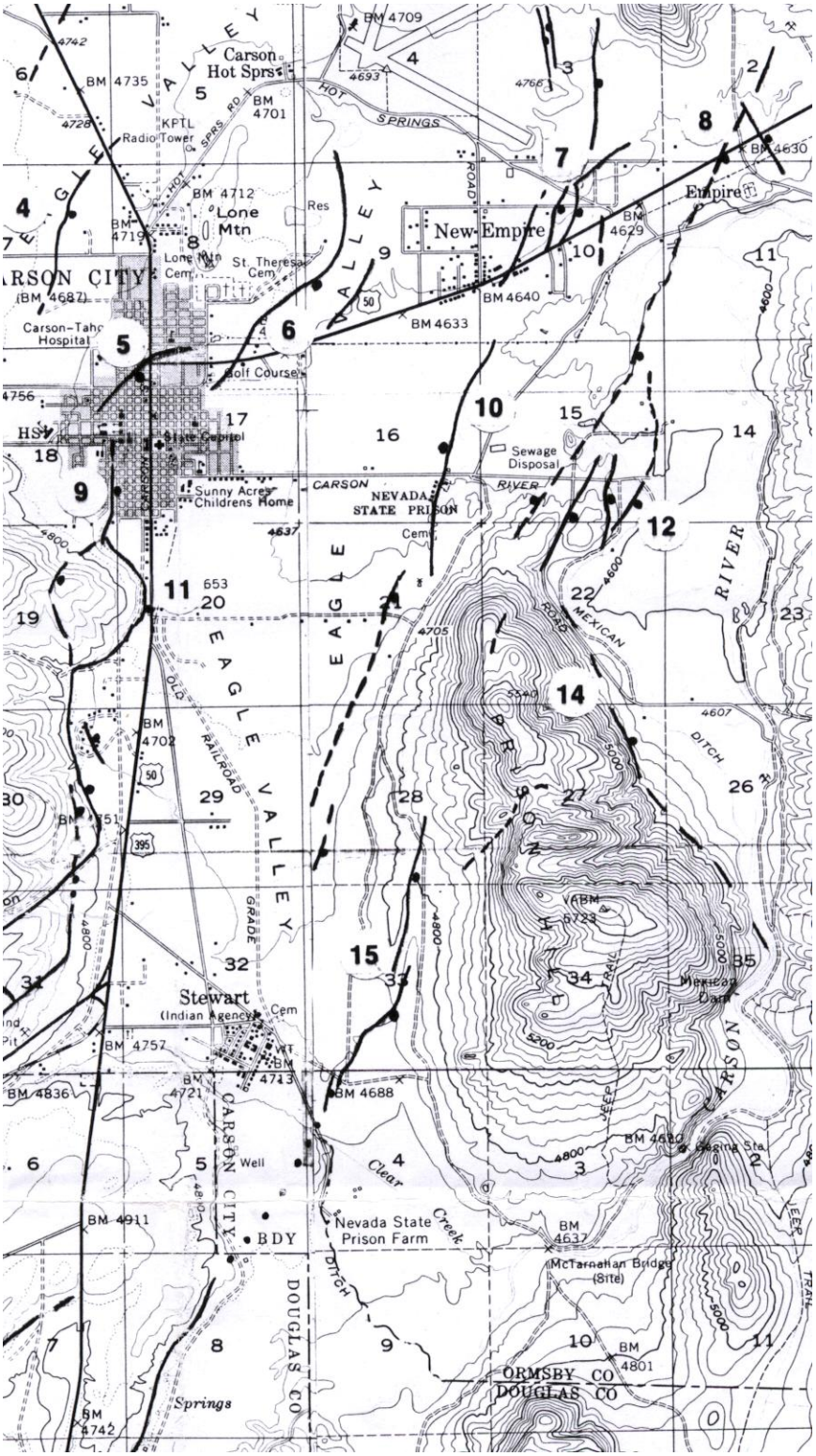
Location and Length

The Indian Hill fault zone splays off of a salient in the Genoa fault, bounds a low set of hills in front of the Carson Range known as Indian Hill, partly splays into these hills. The fault continues east, and after crossing Clear Creek where fault expression has been eroded away or buried by young alluvium, forms a couple back-facing, down-to-the-east fault scarps in the western flank of Prison Hill. The fault zone effectively separates Carson Valley from Jacks Valley, Indian Hills, and Eagle Valley to the north (where Carson City is located).

The end-to-end distance of the Indian Hill fault zone is 13.5 km, from the Genoa fault to the western flank of Prison Hill. It is possible the fault zone continues to the north further, involving additional faults in the northwestern flank of Prison Hill, and possibly through the hill itself; this could extend the fault zone 7.5 km more in length. It is difficult to subdivide the fault zone further for a minimum length, but perhaps rather than directly intersecting the Genoa fault, it intersects the Carson City fault, and that intersects the Genoa fault; this scenario reduces the length by about 2.5 km, for a minimum length of 11 km.



Location map of the Indian Hill fault zone from Ramelli and others (1994). The location of Trench 5 of Trexler and Bell (1979) is shown. The Indian Hill fault continues to the northeast into the western flank of Prison Hill (off of figure and not shown)



Compilation of Quaternary faults in the Carson City area illustrating possible northeastern extensions of the Indian Hill fault zone. The Indian Hill fault zone is labeled "15" and continues to the southwestern part of the figure. Inferred faults are uncertain in existence and/or activity. Faults appear to surround northern Prison Hill and occur in eastern Eagle Valley.

Fault traces of the Carson City fault are labeled "5, 6, 9, 11" and it continues to the southwest.

Figure from dePolo (1996).

Major Fault and Paleoseismic Investigations (chronological order)

Pease, R.C., 1979a, Scarp degradation and fault history south of Carson City, Nevada: University of Nevada, Reno, Masters Thesis, 90 p.

Trexler, D.T. and Bell, J.W., 1979, Earthquake hazard maps of Carson City, New Empire, and South Lake Tahoe Quadrangles: Nevada Bureau of Mines and Geology Final Technical Report to the U.S. Geological Survey Earthquake Hazard Reduction Program, 43 p.

Bell, J.W. and Pease, R.C., 1980, Soil stratigraphy as a technique for fault assessment in the Carson City area, Nevada, *in* Proceedings of Conference X, Earthquake Hazards along the Wasatch, Sierra Nevada frontal fault zones: U.S. Geological Survey Open-File Report 80-801, p. 577-600.

Geomorphic Expression

The Indian Hill fault zone is expressed as compound fault scarps, hillslope scarps and benches, oversteepened hillslope bases, back-facing fault scarps, fault facets as much as 122 m high, small, tectonically terraced alluvial deposits, and springs. Pease (1979a) noted that there are three to four bevels on fault scarps along the Indian Hill fault, and suggests that in many places the scarp was formed by three to four events. Pease (1979a) also noted a single event scarp with no bevel that crosses mid to late Holocene alluvium, and is the youngest event along the fault. Compound fault scarps have total displacements as much as 5.1 m, and single-event scarps are about 1 m high (Pease, 1979a). Pease (1979b) shows different parts of the Indian Hills fault zone with different most recent events ages, as if the zone was discontinuously broken during the last event; this was based on interpreting the age of the scarp from scarp morphology.

Near the intersection with the Genoa fault are Hobo Hot Springs, which come up along the combined Indian Hill and Carson City fault zones.

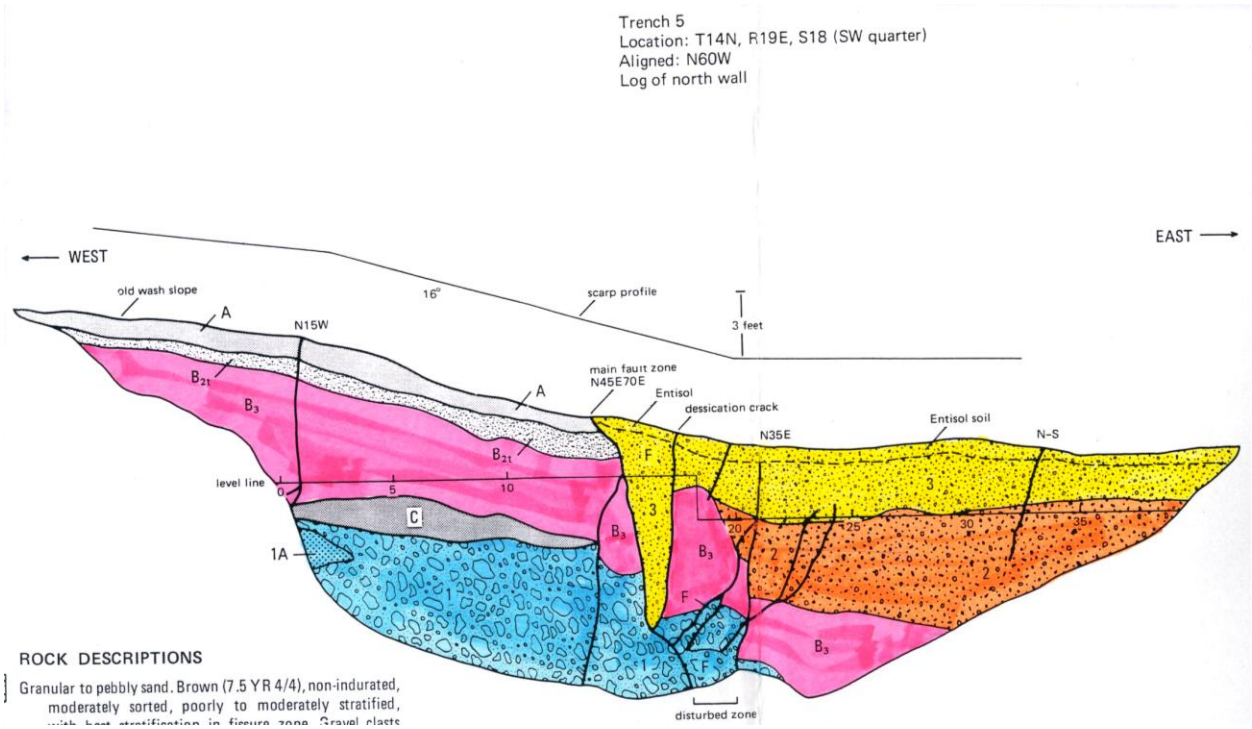
Structural Description

The Indian Hill fault zone has been mapped at a scale of 1:24,000 by Pease (1979b), Bell and Trexler (1979), and Garside and Rigby (1998). It is a normal dip-slip fault zone with down-to-the-east or down-to-the-south displacement. Because of its northeast orientation, it is possible there is a left-lateral component as well. The overall trend of the fault zone is N40ºE, but locally, fault strikes vary from EW to NS. The fault zone is relatively simple and continuous, generally consisting of a single fault, except in the central part of the zone where a major fault trace splays into Indian Hill and is distributed into multiple traces.

Low fault-bound hills continue to the northeast along the main fault. The northern part of the fault zone projects across the river to down-to-the-east, back-facing scarps in the western flank of Prison Hill (dePolo, 1996). If Prison Hill did not exist, a further northeastern extension would seem likely because these faults are aligned with the Indian Hill fault zone and are largely down-to-the-east. It is not clear how much of a structural interruption Prison Hill represents in this northeastern swath of faults.

Earthquake History

There has been limited fault exploration of the Indian Hill fault zone. Trexler and Bell (1979) and Pease (1979a) dug two trenches across the central part of the fault zone and Pease (1979a) logged these (Trexler and Bell, 1979; Trenches 5 and 6) and additionally logged a utility trench across the fault (Pease, 1979a; Trench 1). The same logs are present in both studies, and further discussed in Bell and Pease (1980). They found evidence for two paleoearthquakes and for a hiatus in fault activity prior to these two events. This review will focus on Trexler and Bell's (1979) most informative trench, Trench 5. The other trenches support the history developed at Trench 5.



Log of Trench 5 from Trexler and Bell (1979). Unit 3 (yellow – post-PE1) and unit 2 (orange – post-PE2) are the late Holocene, post-event deposits. The argillic horizon is labeled B2t and the B horizon is labeled B3. Unit 1 is a large pebble gravel, unit 2 is a granular to pebbly sand, unit 3 is a granular to pebbly sand. Soil: A horizon, dark reddish-brown (7.5 YR 4/4) loamy with some stones; B2t horizon, yellowish red (5 YR 5/6) sandy clay with blocky to prismatic structure; B3 horizon, strong brown (7.5 YR 4/6) massive, well-indurated, granular sand, contains clay; C horizon, strong brown (7.5 YR 4/6) massive granular sand with a few veinlets of silica .

Trench 5 was dug across a 1-m-high fault scarp and exposes the main fault down-dropping a middle to late Pleistocene surface that is buried by two Holocene packages of alluvium (units 2 and 3) and has a large fissure developed at the fault from the most recent event. The main fault has a strike of N45ºE, and dips 70º south. The middle to late Pleistocene age for the surface is based on a ~30-cm-thick, well-developed, prismatically structured, reddish-colored argillic horizon, that is generally correlated with local soils that are Sangamon to Wisconsin age (Trexler and Bell, 1979; Bell and Pease, 1980). A less-developed B horizon below this is actual offset across the fault and the argillic horizon is not shown on the down-thrown side of the fault.

Bell and Pease (1980) interpret that two events have occurred in the last 12,000 years, with the most recent event being within the last 2,000 to 3,000 years. Trexler and Bell (1979) indicate that both of the recent events occurred within the last 3,000 years (Table 9). The later constraint is based on an Entisol, or incipient soil (A-C profile), formed on unit 3, the upper Holocene alluvium. No soil is mapped as formed in the alluvial package below this, indicating the two events probably occurred relatively close in time. Vertical offsets during the two most recent events are about 1 m each as measured from the trench log. Pease (1979a), Trexler and Bell (1979), and Bell and Pease (1980) all interpret a hiatus on this fault in late Pleistocene to allow the soil (lower B horizon – unit B3) to form across the fault.

Two recent late Holocene events have occurred on the Indian Hill fault, each with about 1 m of vertical offset at the trench site. A hiatus in fault activity of tens of thousands of years may have occurred before that.

Fault Slip Rates

Only a reconnaissance fault slip rate and a single-interseismic interval rate are available for the Indian Hill fault zone. DePolo (1998) estimated a reconnaissance slip rate of 0.2 m/ky for this fault based on maximum facet height and an empirical relationship. A poorly constrained single-interseismic-interval slip rate of 0.3 to 1 m/ky can be estimated for the recent event (1 m slip with an accumulation period of ~1,000 to ~3,000 years, the possible times between these events assuming they both occurred in the last 3 ky). If a hiatus in fault activity occurred before this, then temporal variations in activity appear to be occurring, with a recent cluster of two events.

Earthquake Recurrence Intervals

Given the data at hand, earthquake recurrence along the Indian Hill fault appears to variable, but there is very little information to go on. The most recent interseismic interval appears to be a maximum of a few thousands of years long.

Earthquake Segmentation

The Indian Hills fault zone does not appear to be amenable to breaking it into shorter earthquake segments. The youngest event appears to have broken the southern parts at least, based on very young fault scarps and the trenching data.

An important question for the Indian Hill fault zone is does it co-rupture along with the Genoa fault, and if so how often? The Indian Hill fault zone is structurally connected to the Genoa fault, so a rupture propagating between the two is structurally consistent. The most recent event along the Indian Hill fault zone may have been part of Paleoearthquake 1 along the Genoa fault, but the Entisol developed on the colluvial deposit formed since the most recent event (Indian Hill f.z.) would have to have formed in the last ~600 years (approximate age of the most recent event on the Genoa fault). With two recent events on both the Genoa and Indian Hill faults it is tempting to correlate these. If Pease (1979a) and Bell and Pease (1979) are correct and there was a hiatus of tens of thousands of years on the Indian Hill fault zone, then ruptures have almost certainly occurred on the Genoa fault that did not involve the Indian Hill fault.

Another segmentation question for the Indian Hill fault zone is the existence of a possible northeastern connection to faults in eastern Eagle Valley, or is Prison Hill a large enough disruption in these faults?

Single-Event Displacements

Trench offsets indicate ~1 m of vertical offset per event for the two most recent events (Pease, 1979).

References

Bell, J.W. and Trexler, D.T., 1979, Earthquake Hazards Map – New Empire Quadrangle: Nevada Bureau of Mines and Geology Map 1Bi, scale 1:24,000.

dePolo, C.M., 1996, Local Quaternary faults and associated potential earthquakes in the Reno and Carson City urban areas: U.S. Geological Survey National Earthquake Hazards Reduction Program, Final Technical Report, 50 p.

dePolo, C.M., 1998, A reconnaissance technique for estimating the slip rates of normal-slip faults in the Great Basin [PhD Dissertation]: University of Nevada, Reno, 199 p.

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Nevada Quaternary Fault Working Group **Carson City fault**
FAULT FORM

Fault Name

Carson City fault,
part of the Carson Range fault system
USGS Fault and Fold Database Fault #1653

Introduction

The Carson City fault splays northeast off a salient on the Genoa fault, crosses Indian Hill, and heads to the north, ending in Carson City. This fault poses a near-field shaking hazard and surface rupture hazard to Carson City and the urban corridor to the south. Nevada's State Capitol and Legislative Buildings are within 0.4 km of the Carson City fault, as is the core of Carson City, which is built on its hanging wall. Much of the fault has houses and other buildings built around it (and on it), with rapid encroachment along the southern part of the fault.

Location and Length

The Carson City fault has three different physiographic settings. The southern part is within an uplifted block (Indian Hill), the central part is a range-bounding fault, and the northern portion is an intra-basin fault (within Eagle Valley, where Carson City lies). The photograph, taken looking north towards Carson City and along the Carson Range front, shows these settings. Indian Hill is in the foreground, shadowed scarps from the Carson City fault are in the middle ground as are the hills the fault bounds, and Carson City lies beyond that; Highway 395 is along the right side of the picture. The Indian Hill fault can also be seen in the foreground.

The end-to-end distance of the Carson City fault is 17.5 km, from an intersection with the Genoa fault to the northernmost mapped Quaternary fault trace in Eagle Valley (Pease, 1979a; Trexler and Bell, 1979; Bell and Trexler, 1979). The fault is a fairly continuous trace, and the uncertainty in the length is relatively small. The fault could extend another ~0.5 km to the north, with expression wiped out by recent fluvial activity. The southern end is an intersection with the Genoa fault that can't really increase without rupturing the Genoa fault. The fault might be considered to die out in Indian Hill before it intersects with the Genoa fault, which could make it ~3 km shorter using the southernmost trace mapped by Pease (1979a). Thus, the range in length for the Carson City fault is 14.5 to 18 km.

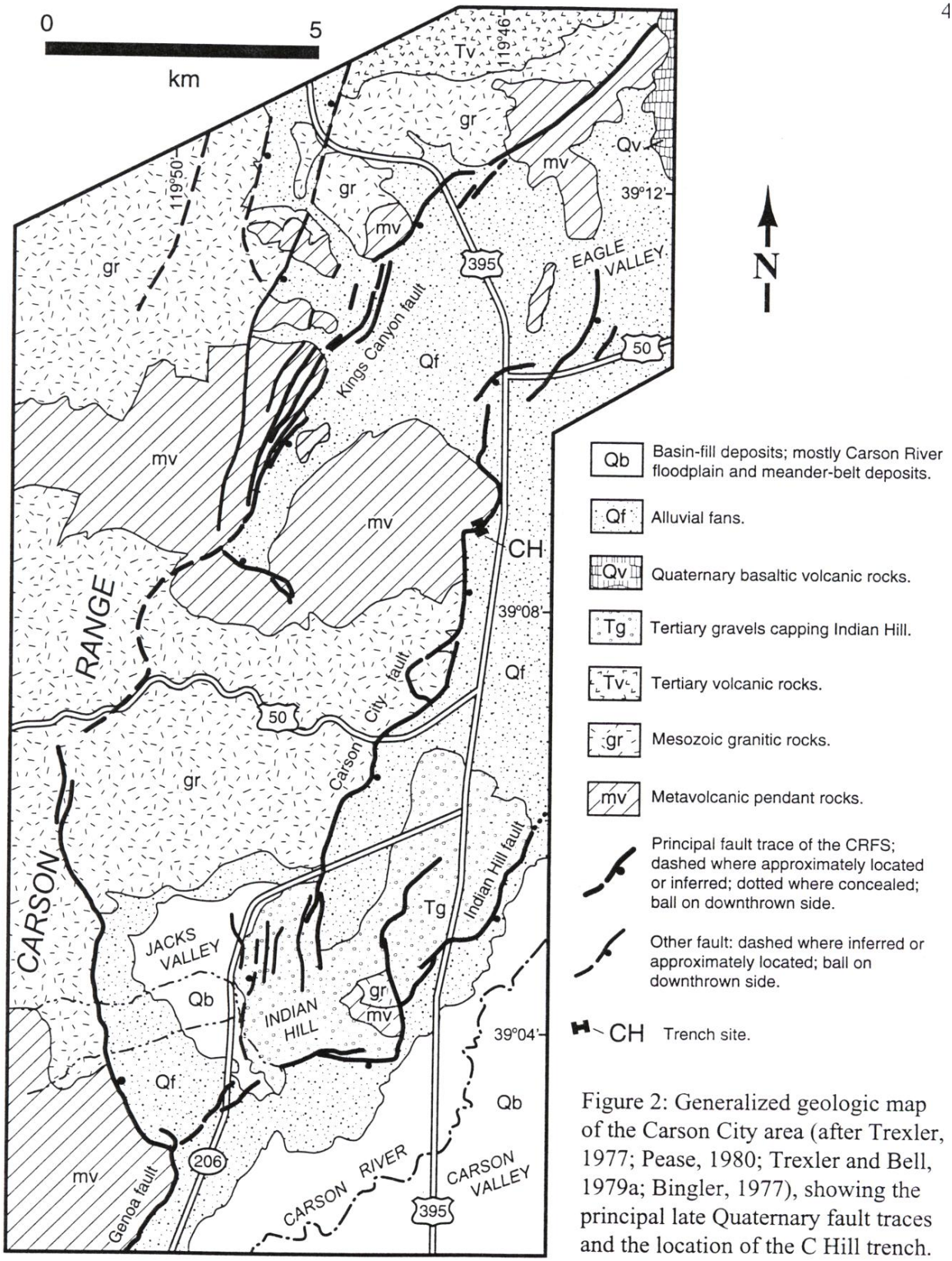


Figure 2: Generalized geologic map of the Carson City area (after Trexler, 1977; Pease, 1980; Trexler and Bell, 1979a; Bingler, 1977), showing the principal late Quaternary fault traces and the location of the C Hill trench.

Figure from Ramelli and others (1999) showing the Carson City fault and trench site.

Major Fault and Paleoseismic Investigations (chronologic order)

Pease, R.C., 1979a, Scarp degradation and fault history south of Carson City, Nevada: University of Nevada, Reno, Masters Thesis, 90 p.

Bell, J.W., Slemmons, D.B., and Wallace, R.E., 1984, Roadlog, Reno to Dixie Valley-Fairview Peak earthquake areas, in Lintz, J. Jr., ed., Western Geological Excursions: Geological Society of America 1984 Annual Meeting field guidebook, v. 4., p. 425-472 [reported trenching work by Pease, 1979, unpublished].

Ramelli, A.R., dePolo, C.M., and Bell, J.W., 1999, Paleoseismic studies of the northern Sierra Nevada Frontal fault zone: Nevada Bureau of Mines and Geology, Final Technical Report to the U.S. Geological Survey National Earthquake Hazards Reduction Program, 16 p.

Geomorphic Expression

Geomorphic features along the Carson City fault are well-developed and distinct, attesting to a fairly active, late Quaternary fault. The fault has fault scarps from the last event that can be seen continuously along Indian Hill and the southern part of the central section of the fault. Pease (1979b) commented that three bevels can be seen in fault scarps within Indian Hill, indicating a late Pleistocene and two Holocene events. Within Carson City, the famous Bonanza Street scarp is a northerly trending fault scarp through town, as much as 13 m high, in early Quaternary deposits (Kirkham, 1976; Trexler, 1977). The fault associated with the Bonanza Street scarp is a groundwater barrier and trees along it grow larger that surrounding trees. The northernmost fault expression in town is a scarp as much as 5 m high in late Quaternary alluvium (Kirkham, 1976; Trexler, 1977).

The central part of the fault bounds a short range front and has fault facets, as much as 110 m high, oversteepened range bases, side-hill scarps and benches, and compound scarps. A low tectonic trim line is present just south of “C Hill”.

There are two hot springs proximal to the Carson City fault. Hobo Hot Springs is near where this fault intersects the Genoa fault and the Carson City Hot Springs lie about 0.7 km north-northwest of the north end of the Carson City fault (in the footwall?).

Structural Description

Overall the Carson City fault is a pretty straight feature with a trend of N24ºE, but in detail there are multiple fault traces, bends, and steps. The fault zone has been mapped in its entirety at a scale of 1:24,000 (Pease, 1979a; Trexler and Bell, 1979; Bell and Trexler, 1979). The southern intersection with the Genoa fault is a little complicated, and might

be an issue of semantics. The Carson City fault can be considered to intersect the Indian Hill fault just north of Hobo hot springs, sensu strictu, just before that fault intersects the Genoa fault, or the Carson City fault can join with the Indian Hill fault to the Genoa fault intersection (the Indian Hill fault is more continuous with this short connecting fault and the Carson City fault is more on-line). Either way, both faults are structurally linked to the Genoa fault. The northern end of the fault appears to die out within northern Eagle Valley.

The sense-of-displacement of the Carson City fault is normal dip-slip, although given its orientation it might have a left-lateral component (especially along the northeast striking parts). The Carson City fault is down-to-the-east over most of its extent, the only possible area of exception being near the intersection with the Genoa fault. The width of the fault where there are subparallel faults in Indian Hill is as much as 1.4 km.

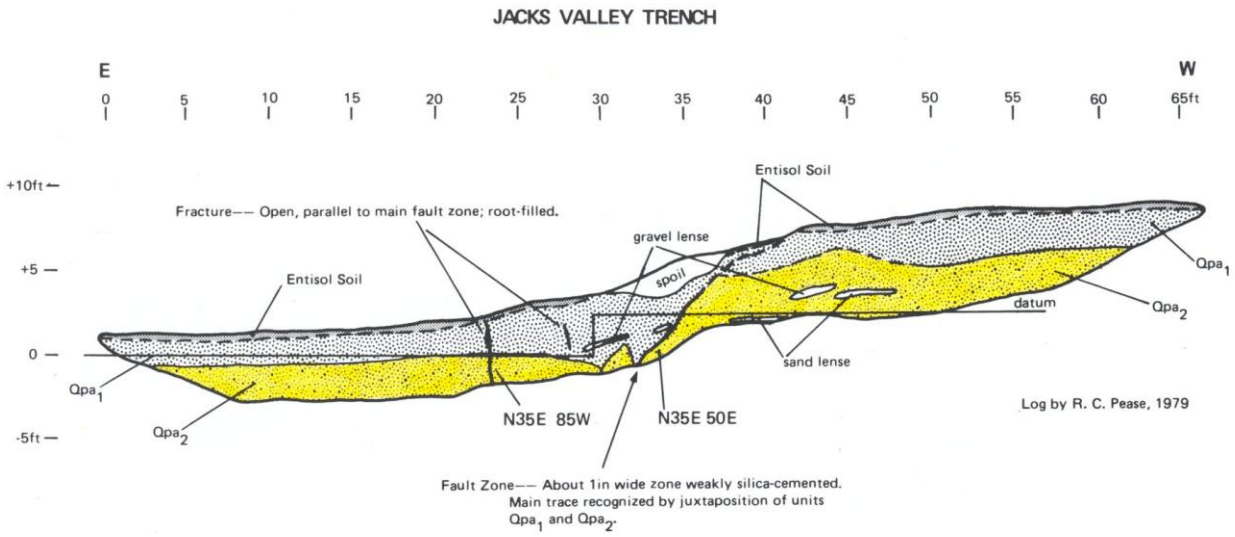
There are three overall strikes of the Carson City fault. The southern part in Indian Hills has a strike of ~N26ºE, the central part along the range front and into southern Carson City is ≈N5ºE, and along the northern portion has a strike of ~N44ºE (the very northernmost part hooks back to the north). This more northeasterly strike at the north end is subparallel to, and likely influenced by, the Carson lineament, a northeast-striking structure with its western end ostensibly terminating in Eagle Valley.

Earthquake History

There have been two major paleoseismic studies along the Carson City fault, Pease (1979b) and Ramelli and others (1999). Pease did scarp morphology studies along the southern part of the fault and a trench study to confirm the most recent age of faulting (Pease, 1979a). Ramelli and others (1999) trenched a young scarp along the Carson City fault and were able to develop timing constraints on the last two paleoearthquakes.

Pease (1979b) examined fault scarp at Indian Hill and elsewhere along the Carson City fault and noted that the fault offsets Holocene alluvium, and that fault scarps have three bevels indicating three late Pleistocene or Holocene events (Pease calls fault this “Fault 2”). Total offset of these three events is estimated to be 3.3 to 8.5 m based on surface offsets (Pease, 1979). Pease (1979b) notes that soils in deposits that are offset by these events are poorly developed Entisols and are no more than 4,000 years old, and infers that the three most recent events along the southern Carson City fault are younger than 4,000 years as well.

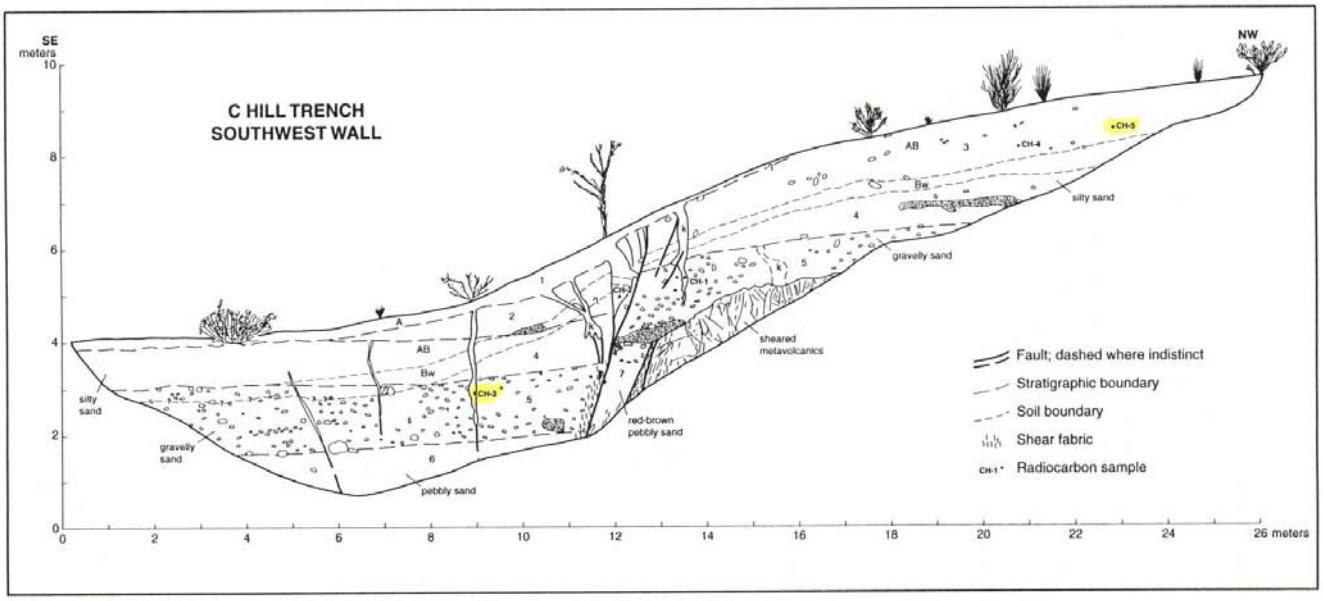
Pease (1979 – unpublished, presented in Bell and others, 1984) had a trench excavated across a 1-m-high scarp in Holocene alluvium to verify the most recent activity of the Carson City fault (this trench was located near the intersection of Highway 206 and the fault – see map). This log was published in Bell and others (1984) and re-excavated for the associated field trip. The trench Holocene deposits (only an A-C soil profile) are offset by the fault and elsewhere Pease obtained a radiocarbon date of 7,140 ±400 ybp from a faulted fan as additional confirmation. The displacement along the fault plane on



Pease's (1979 unpublished) trench log is 1.8 ±0.5 m for a single event (1.2 ±0.4 m vertical).

Trench log for the Jacks Valley trench along the Carson City fault. The log was made by Pease (1979 unpublished work) and published in Bell and others (1984). Qpa1 is a brown muddy coarse sand and Qpa2 is a brown sandy pebble gravel.

Ramelli and others (1999) trenched a small scarp on the south side of a prominent hill, just southwest of Carson City, called "C Hill". The trench exposed poorly stratified alluvial and colluvial deposits that overlie, and are faulted against, sheared metamorphic rocks (Ramelli and others, 1999). A narrow fault zone juxtaposes alluvium against bedrock, and breaks up near the surface into several paleofissures; 2- to 3-m-deep paleo-fissures are also present in the hanging wall and immediate footwall. Ramelli and others (1999) identified evidence for three paleoearthquakes in the C Hill trench, and were able to constrain the age of the two most recent events (PE1 and PE2).



Trench log from the C Hill trench showing evidence of two recent events along the Carson City fault (Ramelli and others, 1999).

Paleoearthquake 1

The main fault zone and several extension fissures offset all but the youngest alluvial deposits, and extend to near the ground surface (Ramelli and others, 1999). A young colluvial deposit has formed and the fissures have filled since PE1, but these deposits lack any soil development and the colluvium is present only as a thin layer that mantles the scarp and hanging wall. Ramelli and others (1999) collected a piece of charcoal from near the bottom of a fissure formed during PE1 that had a radiocarbon date of 390 ±40 ^{14}C ybp; this date is deemed to closely approximate the age of the most recent event along the Carson City fault because the charcoal must have been sitting on the surface when the event occurred and fallen in immediately to have ended up near the bottom of the fissure (Ramell and others, 1999). This date is calendar corrected to 316 – 513 cal. ybp using Stuiver and Reimer (1993) and Reimer and others (2004). The vertical offset could not be tightly constrained but is estimated for PE1 to be 0.7 ±0.3 m, which includes some displacement that was likely accommodated by distributed, non-brittle deformation, as evidenced by extensional fissures (Ramelli and others, 1999).

Paleoearthquake 2

Evidence for PE2 includes offset and fault buttressed deposits and a colluvial wedge (unit 2; Ramelli and others, 1999). Prior to the event, over two meters of undisturbed alluvium crossed the site (units 3, 4, and 5). Although the offset could not be tightly constrained, PE2 offset this alluvium vertically by 1.2 ±0.3 m, with most of the offset along a single, discrete fault trace (Ramelli and others, 1999). The original fault scarp was smoothed

and a cambic soil horizon formed within it (a cambic horizon is a young soil with a slight color change from infiltrated silts).

PE2 offset alluvium that has a radiocarbon date of 2,590 ±130 ^{14}C ybp, indicating the event was after 2,348 – 2,953 cal. ybp (using Stuiver and Reimer, 1993 and Reimer and others, 2004).

Paleoearthquake 3(?)

When PE2 is removed, older alluvium in the trench (unit 6) is left in fault contact formed during an earlier earthquake (Ramelli and others, 1999). Erosion likely erased the top of this deposit before unit 5 was laid down across the site. The displacement and age of this earlier event are unknown.

Fault Slip Rates

There is only a single-earthquake interval rate and a reconnaissance rate available for the Carson City fault. Using the two most recent events from the trenching data (Ramelli and others, 1999), 0.4 to 1 m of offset occurred following 1,835 to 2,637 years of "strain accumulation". This is equivalent to a fault slip rate of 0.15 to 0.54 m/ky. DePolo (1998) estimated a reconnaissance slip rate of 0.2 m/ky for the Carson City fault based on maximum basal fault facet height and an empirical relationship.

Earthquake Recurrence Intervals

Only a single interseismic interval between PE2 and PE1 is available for the Carson City fault. Using the range in calendar corrected constraining dates, the range of years for this interseismic interval are 1,840 to 2,640 years.

Earthquake Segmentation

The Carson City fault does not appear to be amenable to breaking it into shorter earthquake segments. The youngest event appears to have broken the southern and central parts at least, based on very young fault scarps and the trenching data.

The question for the Carson City fault is does it co-rupture along with the Genoa fault, and if so how often? The Carson City fault is structurally connected to the Genoa fault, so a rupture propagating between the two is structurally consistent. The most recent event along the Carson City fault seems to have been part of the most recent event along the Genoa fault, at least the timing is right. Evidence from the trench is consistent with Paleoearthquake 2 along the Carson City fault being coincident with the penultimate event along the Genoa fault as well. But does the Carson City fault ever rupture

independent of the Genoa fault? If so, what percentage of the time is it independent and what percentage does it join with the Genoa fault? The seismic hazard analysis is going to need a range of possibilities to analyze. Evidence indicates that the Carson City fault is likely not 100% independent of the Genoa, and has possibly ruptured the last two out of two events along with the Genoa fault.

Single-Event Displacements

There are three estimates of single event displacements from the two trench studies. Pease (1979, unpublished – reported in Bell and others, 1984) exposed about 1.5 ±0.3 m of vertical offset during the most recent event. Ramelli and others (1999) measured 0.7 ±0.3 m and 1.2 ±0.3 m vertical offsets from PE1 and PE2, respectively, at the trench site.

The range of single-event vertical offsets measured along the Carson City fault is 0.7 – 1.5 (0.4 to 1.8 m – considering uncertainties). The maximum offset along the fault may not have been measured, however.

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Nevada Quaternary Fault Working Group **Kings Canyon fault zone**
FAULT FORM

Fault Name

Kings Canyon fault zone, part of the Carson Range fault system
USGS Fault and Fold Database Fault #1654

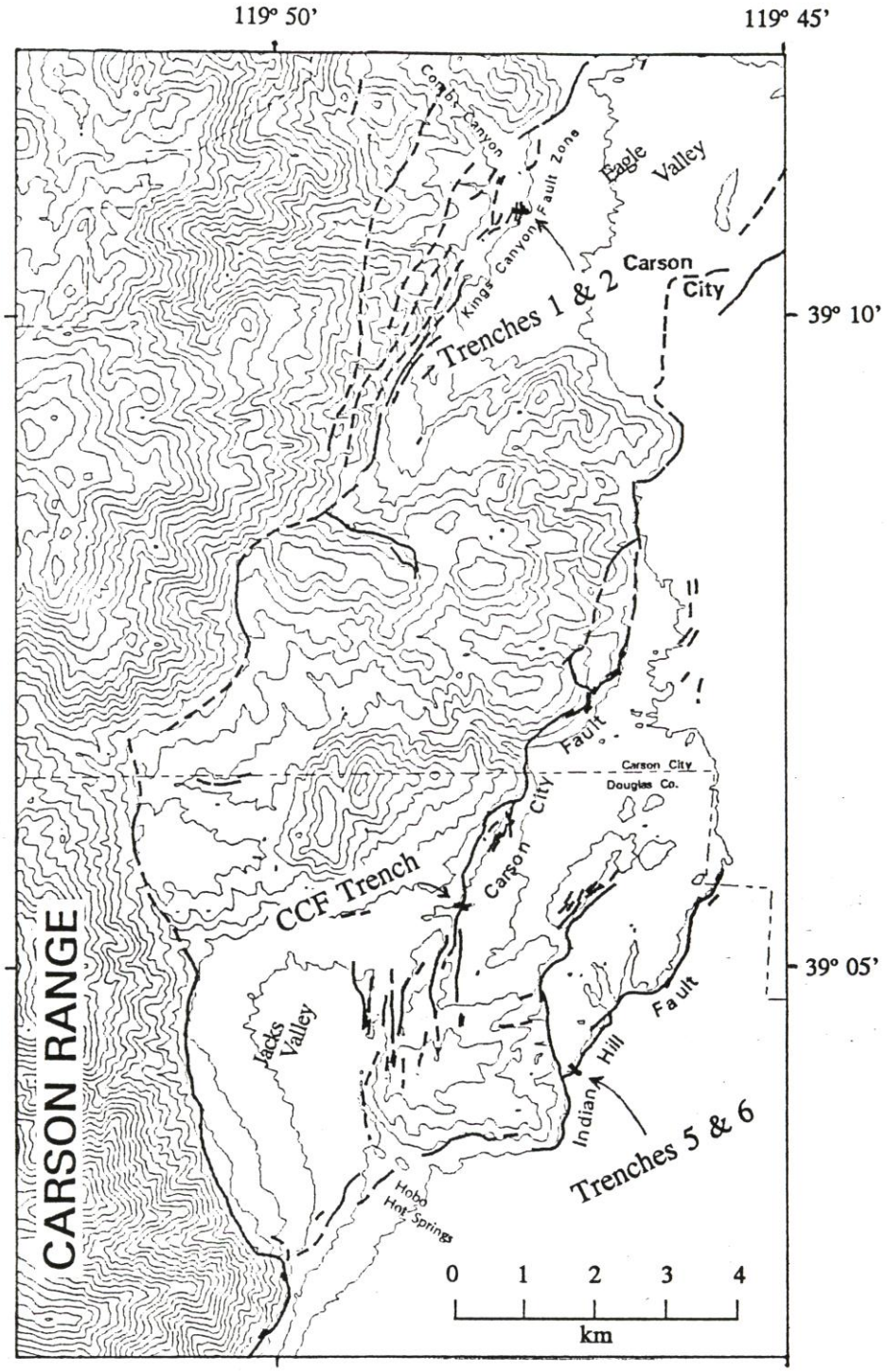
Introduction

The Kings Canyon fault zone is the westernmost of three faults that the Genoa fault splits into at its north end. It is has a range-bounding position over much of its reach, but is commonly a zone of faults, including faults within the range front. The Kings Canyon fault zone is a major hazard to Carson City, which is located on its hanging wall. Urban growth is rapid around this fault and it is very close to a small college campus and a major hospital.

Location and Length

The Kings Canyon fault zone bounds a section of the Carson Range. The zone's southern end is near Highway 50 and the northern part hooks to the northeast and bounds part of the southern end of the Virginia Range (this is a transverse ridge that is in the middle of the Carson Range fault system). This fault also bounds the west and northwestern sides of Eagle Valley, where Carson City lies.

The end-to-end length of the fault zone is ~15 km from near Highway 50 to the northern part of the mapped fault trace (as shown on Bell and Trexler, 1979). The Kings Canyon fault zone may wrap around a hill at the south end and directly intersect the Genoa fault or it may die out to the south and step to the right. In either case, this is a possible 2-km extension to the south. To the north the zone could continue beneath volcanic deposits to an adjacent Quaternary volcanic center that is in-line with the fault and is ~2 km further to the northwest. Thus the maximum length of the zone is 19 km. For a minimum, the fault zone's southern end might be moved northward 3 km to end at the terminus of the mapped Holocene section (Trexler and Bell, 1979b), giving a minimum of a 12 km length.



Location map of the Indian Hill fault zone from Ramelli and others (1994). The location of Trenches 1 and 2 of Trexler and Bell (1979) are shown; Trench 3 was just north of Trench 1.

Major Fault and Paleoseismic Investigations

Trexler, D.T. and Bell, J.W., 1979a, Earthquake hazard maps of Carson City, New Empire, and South Lake Tahoe Quadrangles: Nevada Bureau of Mines and Geology Final Technical Report to the U.S. Geological Survey Earthquake Hazard Reduction Program, 43 p.

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Geomorphic Expression

Geomorphic features along the Kings Canyon fault zone include fault scarps, compound fault scarps, hillslope scarps and benches, oversteepened hillslope bases, a graben, and faceted range fronts as much as 244 m high. Several fault traces are within the range front forming benches and steps in ridge lines. The zone crosses a large fan complex in its central part where it was trenched.

Structural Description

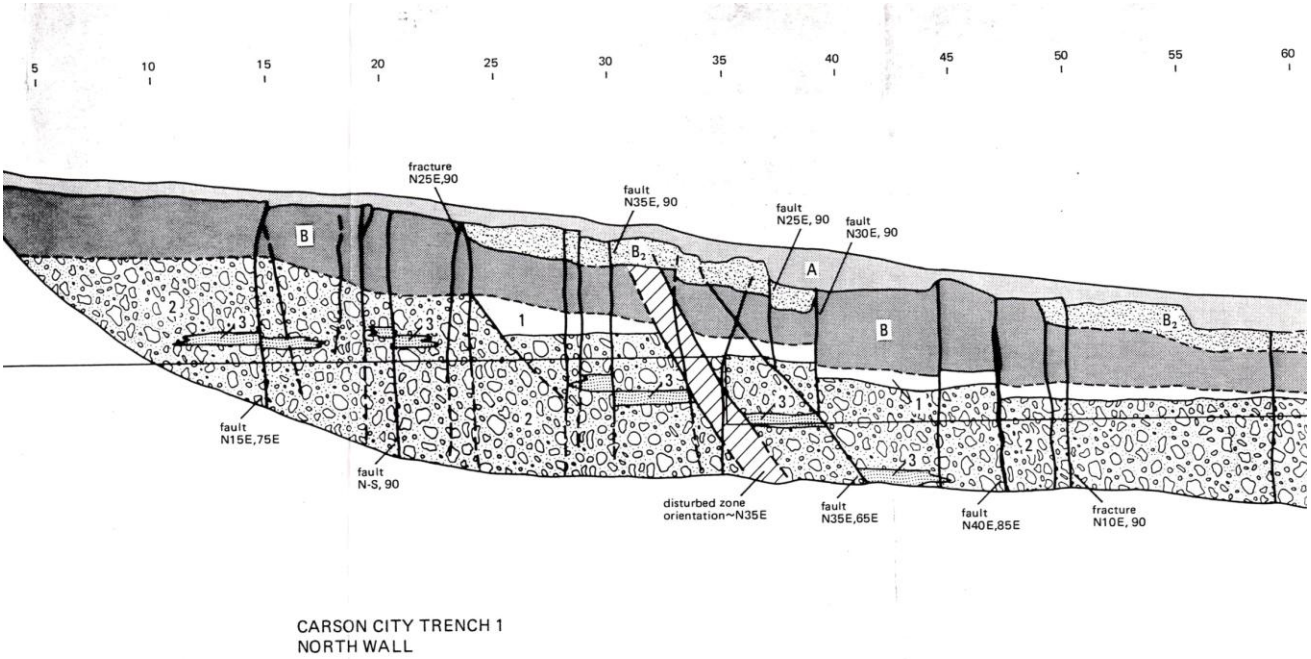
The Kings Canyon fault zone in a down-to-the-east normal dip-slip fault and has been mapped at a scale of 1:24,000 by Trexler and Bell (1979b) and Bell and Trexler (1979). The fault zone is as much as 2 km wide in places where it is made up of several fault traces. The southern end of the zone either connects directly with the Genoa fault by wrapping westward around the range front, or with a cross fault, or it has a 2-km right step to the Genoa fault. The north end dies out in a volcanic field; a volcanic center is on line with the end of the Kings Canyon fault zone, and may be using an extension of the fault as a conduit. Overall the fault strikes about N28ºE, but it turns at its northern reach to N50ºE.

Earthquake History

Trexler and Bell (1979a) excavated four trenches across, and north of, a graben in the central part of the Kings Canyon fault zone (where the zone crosses a fan complex). Trench 1 crossed the western side of the graben and Trench 2 crossed the antithetic scarp on the east side. The paleoseismic history is developed from these two trenches. Trenches 3 and 4 were across northern extensions of these faults. A portion of Trench 3 is shown because it has an interesting offset of the top of a B horizon. Trench 4 had a limited amount of apparent vertical offset, and showed faults with similar relationships as the other trenches. Trexler and Bell (1979a) identified “two movements” in Trenches 1 and 2. At Trench 1 these were estimated to be <5,000 ybp and 5,000 – 12,000 ybp, and at

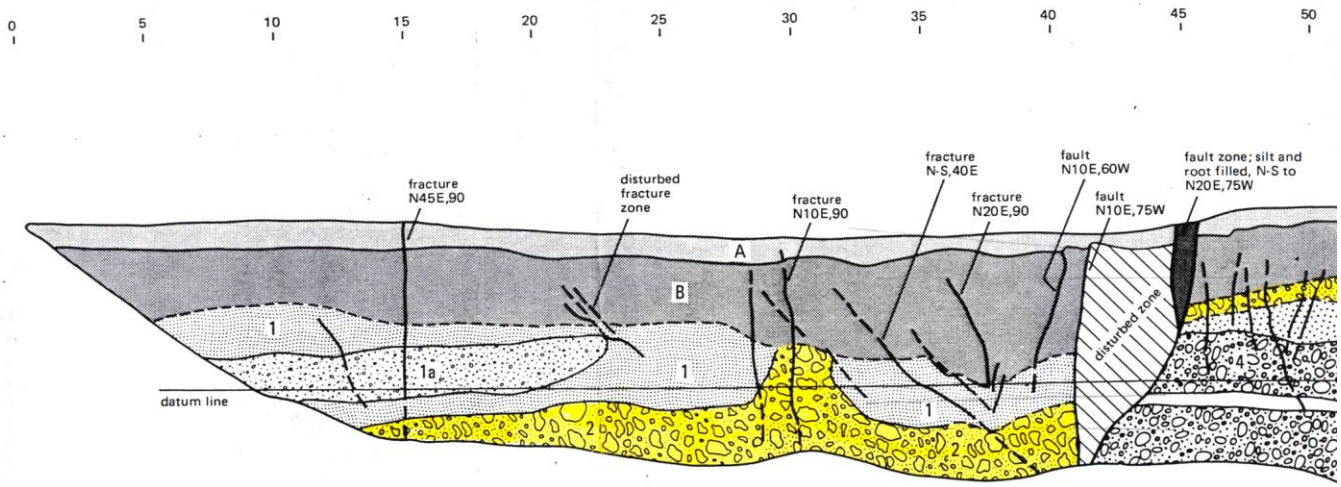
Trench 2 they were <300 ybp and 5,000 – 12,000 ybp (Trexler and Bell, 1979a). The ages are based on soil development. Trexler and Bell (1979a) identified a haploxerollic soil (a cambic soil) overlying a bouldery gravelly grus (also mapped by the Soil Conservation Service). The soil is estimated to be Holocene age, or 5,000 to 12,000 ybp (Trexler and Bell, 1979a).

Trench 1 has an unfaulted A horizon, overlying a fractured and faulted deposit with a haploxerollic soil in it (unit B & B2). Below this is a thin deposit (unit 1) which is down-faulted into the bouldery gravelly grus.



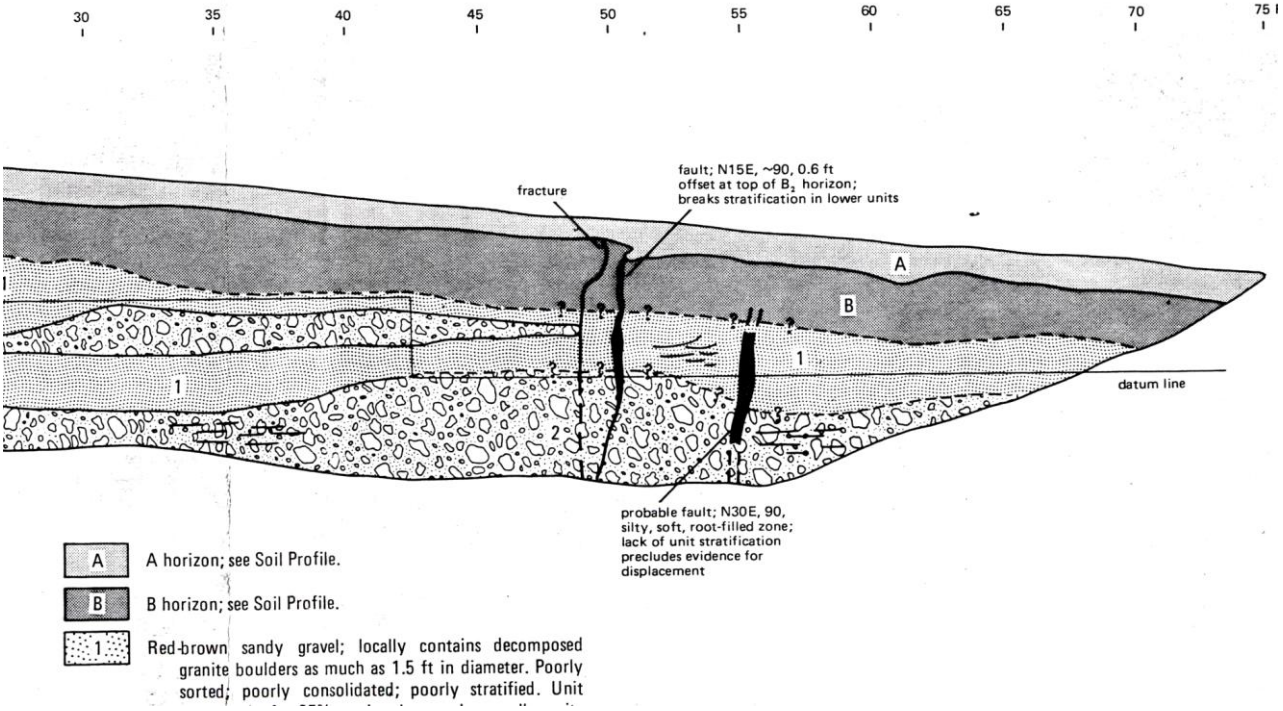
Western part of the Trench 1 log from Trexler and Bell (1979a). In all three logs: A is a light brownish gray, structureless sandy loam A soil horizon; B is a Typic Haploxeroll (cambic) horizon in a sandy loam (color change and possible grain size change); unit 1 is a medium-gray to light red-brown cobbly sandy gravel (poorly sorted, poorly consolidated, and poorly stratified); unit 2 is a light- to medium-gray bouldery gravel that locally contains stratified sand lenses, and is dominantly made up of decomposed granite; unit 3 is a light-gray medium sand lens, 15-30 cm thick; it is well sorted and moderately to well stratified.

Trench 2 has a fault zone and fractures that cross the A horizon, in addition to fractured deposits with a B horizon similar to Trench 1 (Trexler and Bell, 1979a). The fault zone is near the base of a small, 30-cm-high fault scarp, which was created by fault movement; the B horizon is down-dropped a similar amount as the surface proximal to this fault zone. Across the main fault, unit 2 deposits are down-faulted and unit 1 deposits within the graben are buttressed and faulted against the main fault.



Western part of the Trench 2 log from Trexler and Bell (1979a). See Trench 1 log caption for unit descriptions. In addition to these, unit 1a is a light- to medium-gray to light-brown bouldery gravel lens within unit 1; unit 4 is a light- to medium-gray to light brown sandy, bouldery gravel dominated by grus, with a pebble sand layer (white) within it. Unit 2 is colored yellow.

Trench 3 is across a northern extension of the fault in Trench 1. Faults are shown as crossing the B horizon, but not the A horizon. One small fault has 18 cm of apparent down-to-the-east displacement of the top of the B horizon, infilled with A horizon material. This was probably created from the penultimate event. Trexler and Bell (1979a) indicate a single event for this trench that is <5,000 years old.



Trench 3 Log of Trexler and Bell (1979a). See Trench 1 log for unit descriptions.

Paleoearthquake 1

Evidence for the most recent event includes a young scarplet at Trench 2 (and elsewhere) and the fault zone crossing the A horizon in that trench (Trexler and Bell, 1979a). Trexler and Bell (1979a) inferred that this scarp must be very young, perhaps <300ybp, because it seemed fresh and is formed in grus deposits that can erode easily. Trexler and Bell (1979b) showed this young offset in two locations along the Kings Canyon fault zone.

Paleoearthquake 2

Paleoearthquake 2 (PE2) caused the larger disturbed zone in the B horizon in Trench 2 and several small factures and offsets of the B horizon in Trenches 1, 2, and 3. In Trench 3, PE2 appears to have offset the top of the B horizon down-to-the-east by 18 cm, and been buried by the A horizon. This event is estimated to be less that 5,000 ybp because it offsets the haploxerollic soil (Trexler and Bell, 1979a).

Paleoearthquake 3

Below the B horizon in Trench 1 is a pebbly sand (unit 1) that is down-faulted about 45 cm vertically into the underlying deposits (unit 2), but the base of the haploxerollic soil is not shown as displaced; elsewhere the base of this soil is shown as offset by PE2. This is evidence for a third paleoearthquake, PE3. Additionally unit 1 is faulted by a disturbed zone in Trench 1 and PE3 has preserved unit 1 within the graben (Trenches 1 and 2). This event is presumably 5,000 – 12,000 ybp, or a little older, because it is below the haploxerollic soil.

Thus, there is evidence for three Holocene(?) events in the trench logs of Trexler and Bell (1979a). It is permissive for the two most recent events on the Kings Canyon fault zone to be northern extensions of the two most recent Genoa fault ruptures. Not all subparallel fault traces were trenched, so there is the possibility of other events along the zone.

Fault Slip Rates

There are no reported fault slip rates along the Kings Canyon fault zone. DePolo (1998) estimated a reconnaissance slip rate of 0.5 m/ky based on correlating fault slip rate with maximum basal fault facet height.

Earthquake Recurrence Intervals

There is not enough information to confidently estimate earthquake recurrence intervals for this fault.

Earthquake Segmentation

The Kings Canyon fault zone is a relatively short fault (~15 km) and does not seem amenable to being segmented with respect to earthquake ruptures.

The question for the Kings Canyon fault zone is does it co-rupture along with the Genoa fault, and if so how often? The Kings Canyon fault zone intersects, or nearly intersects, the Genoa fault, so a rupture propagating between the two is structurally consistent. With two recent late Holocene events on both the Genoa and Kings Canyon faults it is tempting to correlate these, but it is only a permissive correlation at this time.

The Kings Canyon fault zone is structurally an important consideration for the earthquake segmentation of the Carson Range fault system. The largest discontinuity in the Carson Range fault system is where the southern end of the Virginia Range intersects the system. This is a displacement minimum for the fault system in a transverse ridge model. The Kings Canyon fault zone is the main range-bounding fault of the Carson Range fault system south of this transverse ridge, and it curves to the northeast and bounds the southern side of the transverse ridge. In other words, a major part of ruptures propagating up from the south along the Carson Range fault system can be deflected off to the east, away from the system.

Single-Event Displacements

There are no confident single-event displacement measurements known because the fault is complicated with a graben and multiple fault traces that need to be considered when trying to make a displacement estimate. DePolo (1996) profiled a compound fault scarp in the fan south of the graben where the trenches were excavated. The most recent event is expressed as a small scarp with a surface offset of 2.3 ±0.8 m formed in the middle of the compound scarp (dePolo, 1996).

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Nevada Quaternary Fault Working Group **<u>Mt. Rose fault zone</u>**
FAULT FORM
co-prepared by Alan Ramelli

Fault Name

Mt. Rose fault zone, Carson Range fault system
Includes the Washoe Valley, Little Valley, and Virginia Lake fault zones
USGS Fault and Fold Database Fault #1647

Introduction

The Mt. Rose fault zone (northern half of the Carson Range fault system) is the major fault bounding the east side of the northern Carson Range. The fault zone forms the basin where Reno, the second most populous area in Nevada, lies. Based on the effects from historical earthquakes (e.g., April 24, 1914 Reno earthquake), the fault poses a significant hazard to western Nevada, the northern Sierra Nevada, and the Great Valley of California.

Trenching studies have documented three to four Holocene paleoearthquakes along the Mt. Rose fault zone, and recent trenches dug by geotechnical consultants have added to the database.

Location and Length

The Mt. Rose fault zone extends from southernmost Washoe Valley northward into downtown Reno, for an overall length of ~34 km. In Washoe Valley, the zone includes an 11-km long frontal fault (Washoe Valley fault) and a subparallel fault within the range (Little Valley fault); taken together, these two faults have a length of ~17 km. The northern part of the zone includes an 8-km long frontal fault, several synthetic faults within the range, and a complex, distributed zone of nested graben in the hanging wall

(total length of ~25 km).

Major Fault and Paleoseismic Investigations (chronological order)

Schilling, J. and Szecsody, G.C., 1982, Earthquake hazard maps, Mt. Rose NE and Reno NW 7½-minute quadrangles: Nevada Bureau of Mines and Geology, Final Technical Report, U.S. Geological Survey National Earthquake Hazard Reduction Program, contract no. 14-08-0001-19823, 63 p.

Ramelli, A.R. and dePolo, C.M., 1997, Trenching and related studies of the northern Sierra Nevada range-front fault system: Nevada Bureau of Mines and Geology, Final Technical Report, U.S. Geological Survey National Earthquake Hazard Reduction Program, contract no. 1434-95-G-2606, 21 p.

Ramelli, A.R., dePolo, C.M., and Bell, J.W., 1999a, Paleoseismic studies of the northern Sierra Nevada Frontal fault zone: Nevada Bureau of Mines and Geology, Final Technical Report to the National Earthquake Hazard Reduction Program, contract no. 1434-HQ-97-GR-03043, 16 p.

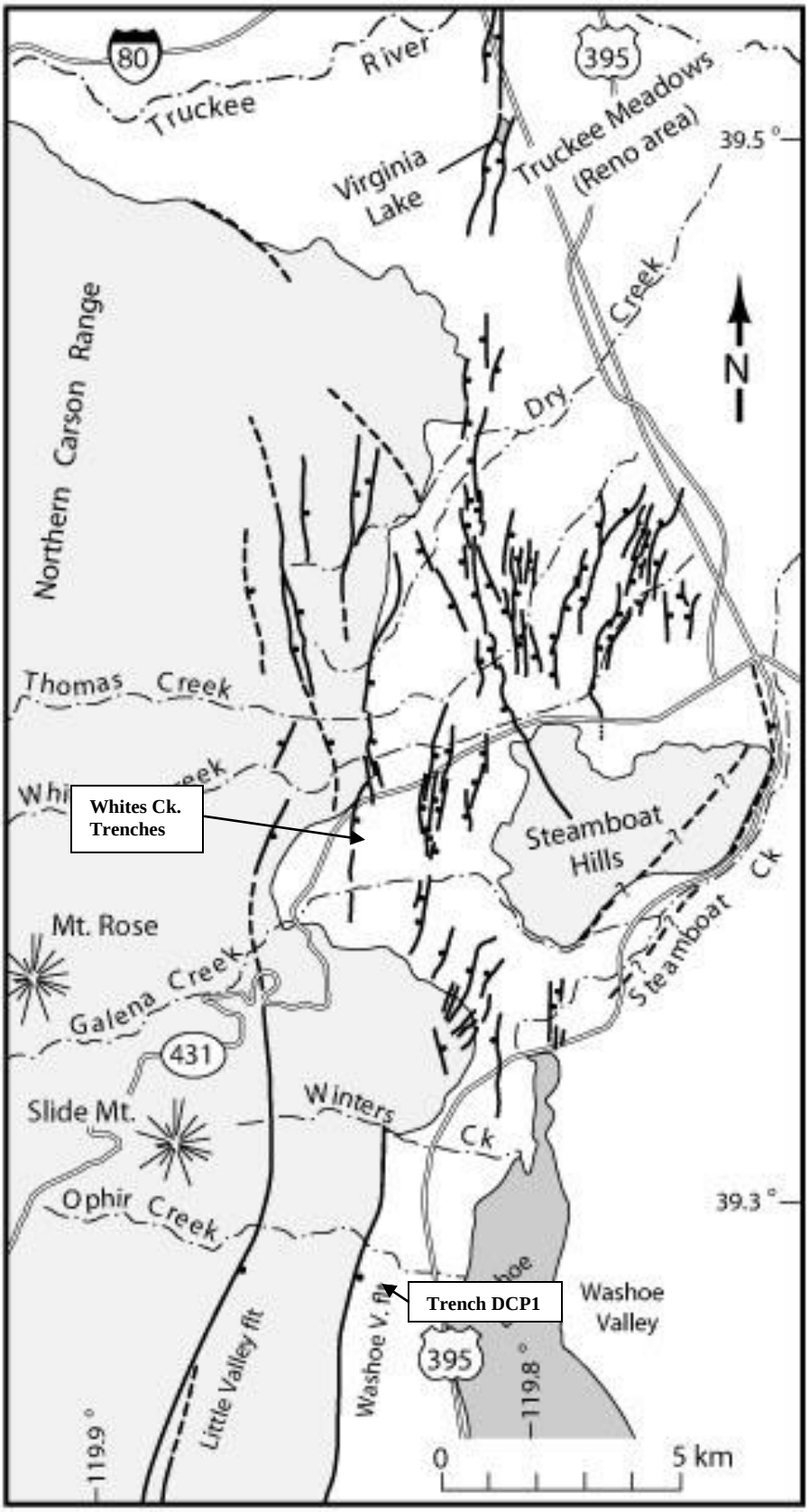
Ramelli, A.R., Bell, J.W., dePolo, C.M., and Yount, J.C., 1999, Large-magnitude, late Holocene earthquakes on the Genoa fault, west-central Nevada and eastern California: Bulletin of the Seismological Society of America, v. 89, p. 1,458-1,472.

Geomorphic Expression

The Mt. Rose fault zone forms faceted range fronts and dip slopes, single-event and compound fault scarps, complex nested graben, faulted inset stream terraces, spring alignments, and vegetation lineaments. Although distinct fault facets are present, such as the eastern front of Slide Mountain, many of the northernmost slopes along the Carson Range that appear to be facets are dip slopes formed on volcanic rocks, tilted by uplift of the Carson Range and activated by normal faults of the Mt. Rose fault zone.

Structural Description

The Mt Rose fault zone is a distributed, down-to-the-east normal dip-slip fault that bounds the northeastern side of the Carson Range. In places the zone has a shattered appearance with swarms of sub-parallel and anastomosing faults, such as the Mt. Rose fan area. The fault zone has been mapped at a scale of 1:24,000 by Bingler (1974), Tabor and Ellen (1975), Trexler and Bell (1979), and Szecsody (1983). The fault zone is 2 to 3 km wide within the western flank of the Carson Range, including the range-front fault trace, and becomes very broad (6 to 10 km width) if the Mt. Rose fan faults are included. The overall orientation of the fault zone is N6º-11ºE, but individual fault traces range in strike from northeast to northwest. The range-bounding faults commonly have sections that strike within a few degrees of north-south.



Strip map of the northern Carson Range fault system and approximate locations of trenches (Ramelli and others 1994).

Washoe Valley (to the left) and Little Valley looking south from Slide Mt (Photograph by Alan Ramelli).

The Mt. Rose fault zone can be divided into two distinctive structural segments. The relatively simple southern segment (Washoe Valley segment) includes two principal faults: a typical range-front fault (Washoe Valley fault) and a subparallel fault that forms a shallow valley (essentially a bench) perched within the range (Little Valley fault). The northern segment (Mt. Rose segment) is a complex, highly distributed fault zone (as much as 10 km wide) that includes a short range-front fault, several generally synthetic faults within the range, and a broad "shattered" zone of nested graben on the Mt. Rose piedmont. These segments are divided at the north end of Washoe Valley, where the Washoe Valley fault abruptly dies out; alternatively, they could be considered to overlap by up to 10 km. A third structural segment, the Virginia Lake fault zone, can be further divided from the Mt. Rose segment.

Despite its relatively short length (~11 km), the Washoe Valley fault forms a prominent range-front escarpment with about 600 m of relief. The Little Valley fault similarly has about 600 m of relief, and net throw across the two faults is more than 1 km. At Winters Creek, where the Washoe Valley fault abruptly dies out, most of the vertical relief steps left to the east flank of Slide Mountain (Little Valley fault).

The Washoe Valley fault is separated from distributed faults of the Mt. Rose segment by a ~2 km gap in obvious recent faulting, while the Little Valley fault overlaps with the Mt. Rose segment by ~6 km. North of Galena Creek, much of the vertical offset on the Little Valley fault steps right to the short (~8 km long) Mt. Rose range-front fault.

The northern part of the Carson Range is nearly entirely composed of Tertiary volcanic rocks, in contrast to the southern and central parts of the range which are dominantly granitic. At its north end, the range dies out into a large, northward-plunging antiform, and is cut by several poorly defined, northwest-striking faults.

Earthquake Segmentation

The Mt. Rose fault zone is separated from the southern Carson Range fault system by a major discontinuity at the south end of Washoe Valley (bedrock high at Lakeview Summit), the Virginia Range transverse ridge This is the largest discontinuity in the Carson Range fault system, and there appears to be a difference in event timing across it (at least for the most recent event). A list of features of this discontinuity that support this being an earthquake segment boundary are:

- Difference in timing of paleoearthquakes on either side
- Virginia Range transverse ridge intersection
- Displacement minimum in Carson Range fault system (~1/2? total displacement)
- Salient in Carson Range fault system
- 3-km left step in range front
- Major faults of the system die out or deflect away towards the discontinuity

The Lakeview Summit discontinuity is the most distinct disruption in the 110-km-long Carson Range fault system and is assumed to be a persistent earthquake segmentation boundary. (see Genoa fault report for additional discussion).

The **Washoe Valley structural segment (**southern part of the Mt. Rose fault zone) consists of two principal, subparallel fault zones, the Washoe Valley and Little Valley faults. The Washoe Valley fault is a range-front fault zone that extends about 11 km along the western side of Washoe Valley. The fault is northerly striking and locally forms a zone up to 300 m wide (Nitchman and Ramelli, 1991). In a few places, fault scarps about 1 m high occur in young fan deposits (Nitchman and Ramelli, 1991). The Little Valley fault lies within the Carson Range, forming a shallow valley perched within the range. The Little Valley fault bounds the eastern front of Slide Mountain, overlapping and merging with the Mt. Rose segment to the north (Ramelli and others, 1994). Fault scarps having a vertical separation of 1.5 – 2 m and maximum scarp angles of 18º to 22º have been mapped along the Little Valley fault (Ramelli and others, 1994).

The **Mt. Rose structural segment** is highly complex and distributed, in contrast to the relatively simple range-front faults along the system to the south. The Mt. Rose segment includes a range-front fault that dies out before reaching the north end of the range, several generally synthetic faults within the range, and a complexly faulted piedmont.

The Mt. Rose piedmont (commonly called the Mt. Rose fan) is largely composed of glacial outwash deposits of Tahoe age or older. The piedmont is broadly warped and cut

by a series of subparallel, nested graben. This piedmont fault zone includes both synthetic and antithetic faults, but in most cases the synthetic faults have larger displacements. The southern part of the piedmont is characterized by a 2.5-km wide nested graben separating Steamboat Hills from the Carson Range (see low sun angle photo to right). North of Steamboat Hills, the piedmont fault zone is about 7 km wide and includes at least five subparallel, sygmoidal graben. These two sections appear to be separated by a northwest-striking, antithetic fault zone. This northwest-striking fault has a left-stepping pattern, suggesting a right-lateral component, and it may also truncate the range-front fault.

A persistent feature of the Mt. Rose piedmont fault zone is a relatively narrow (~0.5 km wide), linear zone of graben, generally located more than 1 km east of the range front. This discontinuous zone includes the central part of the Callahan Ranch graben (above photo) and extends north into Reno, forming the Virginia Lake fault zone.

The **Virginia Lake fault zone** extends north into downtown Reno, to near the Truckee River in the central part of the basin. This fault zone, which has been called the Reno section of the Mt. Rose segment (Ramelli and others, 1994) and the Virginia Lake fault zone (dePolo, 1996), is important due to its proximity to Reno. The Virginia Lake fault zone consists of compound fault scarps, graben, and geothermal and related spring activity. The fault zone appears to pond Holocene alluvium (Bonham and Rogers, 1983) although it is not mapped as offsetting these sediments.

Due to urban development, no suitable trench sites along the Virginia Lake fault zone have been found, although Schilling and Szecsody (1982) examined consultants' trench logs and commented,

> "Faults in the Virginia Lake area (north-central) have been trenched; however, the soil-stratigraphic relations are not shown on the trench logs and they could not be used for age interpretations. It is clear from the soils and geologic maps that these faults have displaced Donner Lake outwash, and they do not cut the Holocene alluvial deposits in the area."

Holocene activity has been documented on many faults in the Reno area that were incorrectly interpreted as lacking Holocene activity during studies conducted in the 1970s and 1980s. It's possible that activity of the Virginia Lake fault zone was also incorrectly interpreted, and the recency of rupture along this part of the system is an open question. Additionally, geothermal activity along the Virginia Lake fault zone indicates open conduits along the fault, possibly from recent fault activity.

Segmentation discussion

The Washoe Valley and Little Valley faults are structurally aligned and nearly continuous with the Mt. Rose range-front fault, so it is likely that the Washoe Valley and Mt. Rose segments rupture together. The total length of the Washoe Valley fault is about 11 km, yet the single-event displacement estimated from trenching along the northern end of this zone is 2 to 2.5 m (Ramelli and others, 1999a). This amount of displacement is inconsistent with the short length of the fault, further supporting the interpretation that it fails with the Mt. Rose segment (at least during recent events). The Virginia Lake fault zone is more aligned with Mt. Rose piedmont faults than the range-front fault, and its activity is poorly understood. Available information suggests relatively low activity on this northern extension of the system, and thus it is unclear how far north recent ruptures of the Mt. Rose fault zone have extended. The Washoe Valley and Mt. Rose segments have both ruptured as least twice in the late Holocene, whereas the Virginia Lake fault zone does not have documented Holocene activity.

Earthquake History

Paleoseismic data for the northern Carson Range fault system come from three areas:

1) At Whites Creek canyon there is a 10-m-high fault scarp on a Tahoe-age glacial outwash terrace, and a small scarp (<1.5 m high) on a young side-channel alluvial terrace. The young scarp was trenched by Schilling and Szecsody (1982), and the larger compound scarp was trenched by consultants and logged by Ramelli and others (1999a).
2) Two trenches were excavated across scarps at Davis Creek Park in northern Washoe Valley: one on a Holocene surface, and one on a late Pleistocene surface (Ramelli and dePolo, 1997).
3) Ramelli (2007, written comm.) has also been investigating consultant's trenches in the Mt. Rose fan area and has developed additional age constraints on the most recent event.

The Washoe Valley and Mt. Rose segments are assumed to rupture together for the following reasons: 1) major fault traces of the two segments overlap; 2) individually, they would be relatively short faults; and 3) offsets are similar along the two range front traces (~2 m/event).

Based on these studies, three and possibly four Holocene earthquakes have been identified along the Mt. Rose fault zone (Ramelli and others, 1999a).

Paleoearthquake Summary:

PE1	690* – 910 ybp (one sigma)
	630* – 930 ybp (two sigma)
PE2	≤1,550 - ≤1,860 ybp or ≥2,330 - ≥2,680 ybp
PE3	≥8,420 - ≥8,590 ybp
PE4	8,400 ybp – latest Pleistocene

* includes mean residence time correction of 100 years.

Paleoearthquake 1

Young surface ruptures are evident in several locations along the Mt. Rose and Washoe Valley sections as a small scarp crossing young alluvial terraces along the main fault, and as steepened faces on compound fault scarps on the Mt. Rose fan (shattered hanging wall of the Mt. Rose fault zone). Potential constraints on the age of this event come from organic material found in fissure fill both along the main fault and faults in the Mt. Rose fan.

The most recent event at the mouth of Whites Creek canyon is expressed by a small scarp (<1.5 m high) crossing a young side-channel alluvial terrace, trenched by Gail Szecsody of the Nevada Bureau of Mines and Geology in 1981 (reported in Schilling and Szecsody, 1982). The trench log is presented in both Schilling and Szecsody (1982) and Bell and others (1984), and radiocarbon dates from the trench were presented in Bell and others (1984). Three units mapped in the trench were labeled the A, B2t, and C soil horizons (see log for descriptions). Two faults both have filled fissures near the surface. The main fault (N15ºW, 71º NE) has about 60 cm of vertical offset, and a secondary fault (N12ºW, 82ºNE) has about 10 cm of offset. All three units were apparently displaced, with A-horizon material filling the fissures. Schilling and Szecsody (1982) also noted a distinct difference in parent material (lower C unit) across the main fault.

A radiocarbon sample from "organic A-horizon-type material" in the lower part of the fissure on the main fault yielded a date of 910±70 ^{14}C ybp, and two combined samples from "carbonaceous materials from secondarily filled burrows or crevasses" yielded a date of 620±70 ^{14}C ybp (Schilling and Szecsody, 1982; Bell and others, 1984). The fissure-fill material may have had some accumulated age, or mean-residence time, prior to the event.

Ramelli (2007, unpublished data) logged two trenches across secondary faults lower on the Mt. Rose fan that exposed fault fissures filled with organic-rich material. One sample from these fissures yielded a date (930 ±60 ^{14}C ybp) virtually identical to that from Szecsody's trench, while the other is only slightly older (1,060 ±70 ^{14}C ybp).

Calibrated Dates that Relate to PE1

Trench #/ Type	Pre/Post	Radiocarbon Date	Calibrated Dates* 1-Sigma Range	2-Sigma Range
WC-T1 bulk	pre/ff	910 ±70 ybp	770 – 913 cal ybp	691 – 934 cal ybp
CR-T12 bulk	pre/ff	930 ±60 ybp	792 – 916 cal ybp	729 – 954 cal ybp
CR-T15 bulk	pre/ff	1,060 ±70 ybp	923 – 1,058 cal ybp	796 – 1,170 cal ybp

* calibrated using Stuiver and Reimer (1993) and Reimer and others (2004).

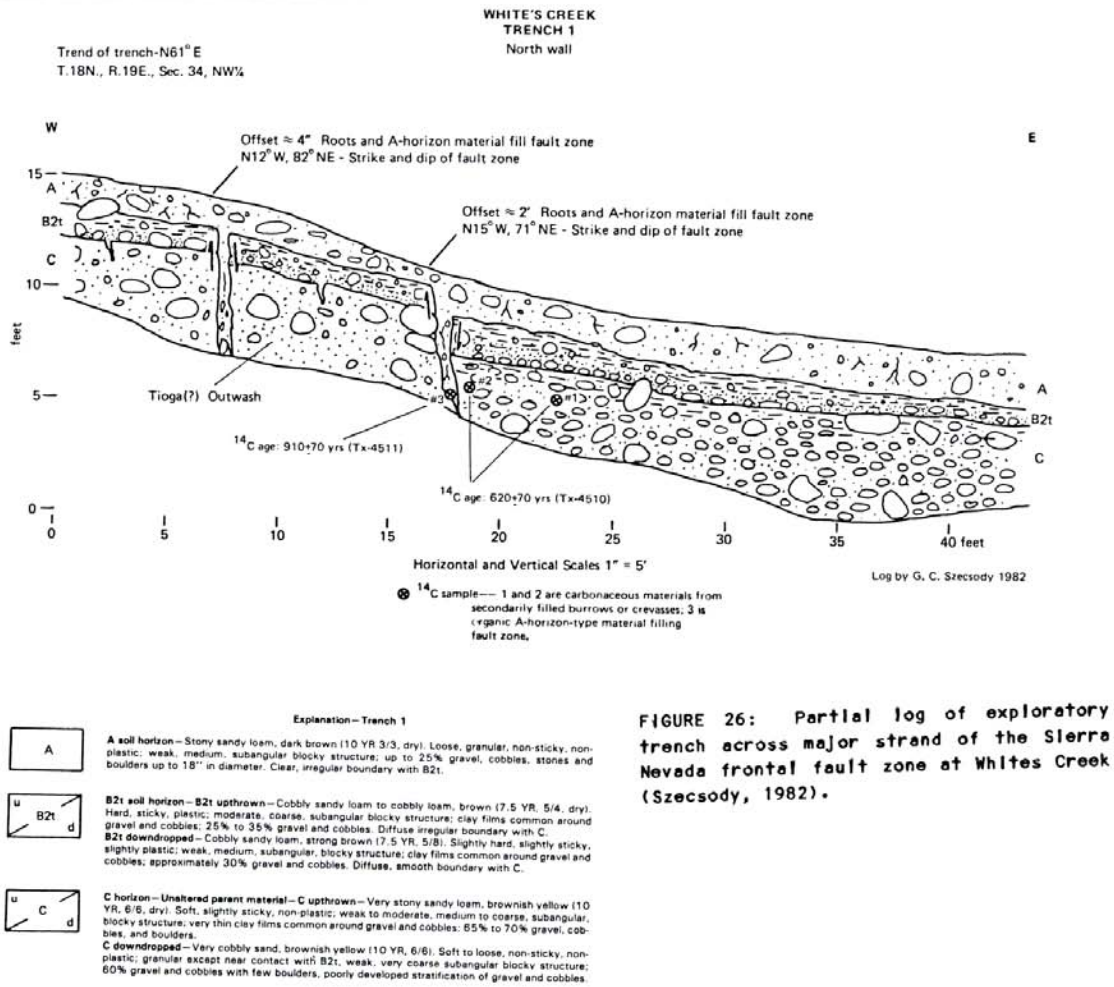


FIGURE 26: Partial log of exploratory trench across major strand of the Sierra Nevada frontal fault zone at Whites Creek (Szecsody, 1982).

Figure from Bell and others (1984)

At 1-sigma, sample CR-T15 falls slightly out of the range in uncertainty of the other two dates, which could be explained by mean residence time. Combining the rounded-off results of the two younger dates, and assuming the sample material was contemporary with surface rupture, the age range for PE1 is 790 – 910 cal ybp (1-sigma), or 730 – 930 cal ybp (2-sigma). Applying a mean residence time correction of 50 to 100 years would indicate ranges of 690 - 860 cal ybp (1-sigma), or 630 – 780 cal ybp (2-sigma).

Paleoearthquake 2

There are two dates potentially constraining the age of Paleoearthquake 2 along the Mt. Rose fault zone, one from northern Washoe Valley and the other from the mouth of Whites Creek canyon.

A trench at Davis Creek Park in northern Washoe Valley, Trench DCP1, exposed a charcoal-rich fan deposit offset by two events (Ramelli and dePolo, 1997). Several charcoal samples were submitted, but some yielded anomalous dates. Three were similar, regardless of their location (see below). An *in situ* burn layer (sample DCP1-1a; 1,780 +/-60 ybp) and a reworked sample from the PE2 colluvial wedge (sample DCP1-25a; 1,770 +/-60 ybp) yielded identical dates, so we consider the combined result of the two (1550 – 1860 cal ybp) to best represent the age of the fan deposit.

A colluvial deposit associated with PE2 exposed in a consultant's trench at Whites Creek yielded a radiocarbon date of 2,370 ± 40 ybp (Ramelli and others, 1999a). The trench was on the north side of Whites Creek and exposed granitic-dominated alluvial fan deposits overlain by volcanic-dominated colluvial deposits derived from the adjacent hillside (Ramelli and others, 1999a). The sample came from the lower-central part of a colluvial-wedge deposit faulted by PE1. Calendar correcting this date gives a range of 2,330 - 2,680 cal ybp (2-sigma). This deposit likely formed shortly after the occurrence of PE2, but could have incorporated older, detrital material.

There is an inconsistency of several hundred years between the dates from Whites Creek and Davis Creek Park. The former (2330 - 2680 cal ybp) should post-date PE2, while the latter (1550 – 1860 cal ybp) should pre-date that event. Either the Whites Creek sample is contaminated with older, reworked material, or the Davis Creek Park samples have lost carbon to groundwater leaching, as suggested by groundwater staining and two charcoal samples that yielded anomalously young ages (Ramelli and dePolo, 1997). Based on the similarity of the Davis Creek Park dates and that one of these samples is from an *in situ* burn layer, Ramelli and dePolo (1997) and Ramelli and others (1999a) assumed the Whites Creek date was contaminated, and interpreted that PE2 occurred after ~1,700 ybp.

Calibrated Dates that Relate to PE2

Trench/#	Type	Pre/Post	Radiocarbon Date	Calibrated Dates* 1-Sigma Range	2-Sigma Range
WC-2	bulk	post	2,370 ±40 ybp	2,342 – 2,458 ybp	2,331 – 2,682 ybp
DCP1-25a	AMS	pre	1,770 ±60 ybp	1,608 – 1,810 ybp	1,543 – 1,857 ybp
DCP1-1a	AMS	post	1,780 ±60 ybp	1,619 – 1,811 ybp	1,553 – 1,862 ybp
DCP1-7C	AMS	post?	2,070 ±60 ybp	1,951 – 2,120 ybp	1,886 – 2,298 ybp

* calibrated using Stuiver and Reimer (1993) and Reimer and others (2004).

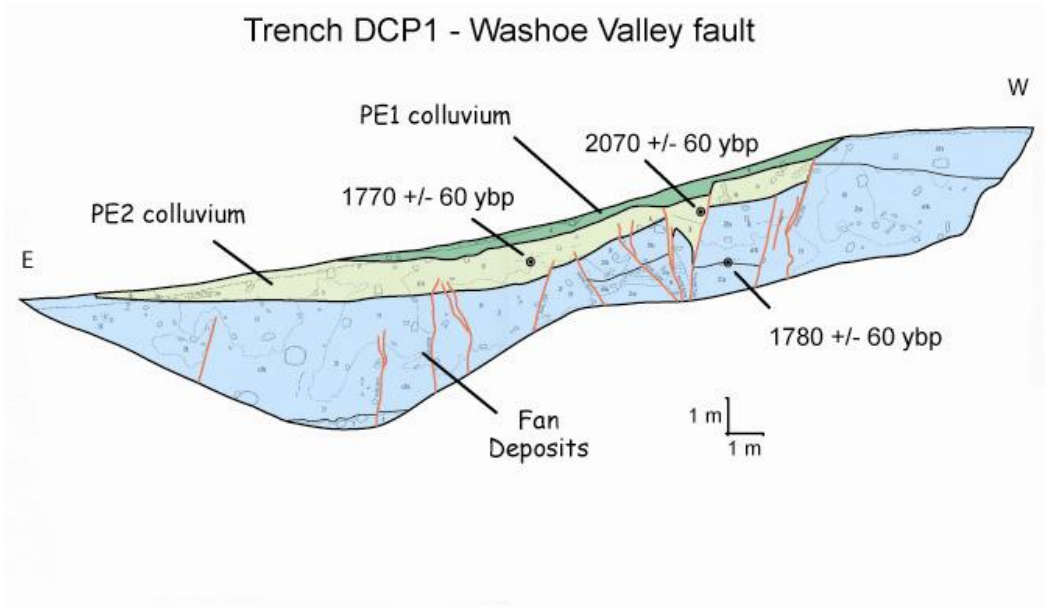


Figure from Ramelli and dePolo (1997); uncorrected radiocarbon dates are shown. Exposed are poorly stratified, bouldery grus deposits.

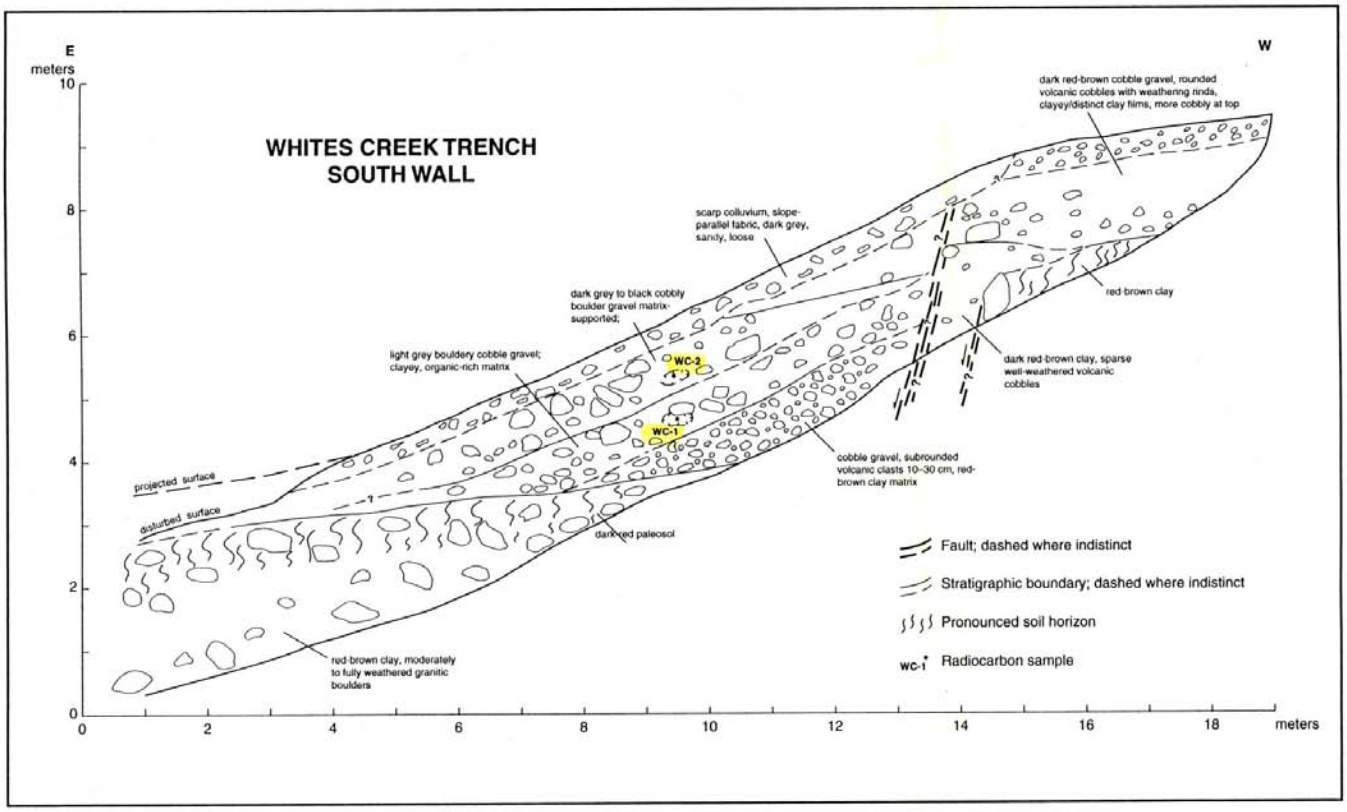


Figure from Ramelli and others (1999a)

Paleoearthquake 3

A third colluvial deposit in the consultant's trench at Whites Creek relates to Paleoearthquake 3 (Ramelli and others, 1999a). A radiocarbon date from a bulk sample taken from near the bottom of this deposit indicates PE3 occurred just prior to ~8,400 ybp (8,420 - 8,590 cal ybp, 2-sigma). Holocene ages are supported by the weak soil development in this and overlying units.

Calibrated Dates that Relate to PE3

Trench/#	Type	Pre/Post	Radiocarbon Date	Calibrated Dates* 1-Sigma Range	Calibrated Dates* 2-Sigma Range
WC-1	bulk	post	7,720 ±50 ybp	8,444 – 8,546 ybp	8,417 – 8,589 ybp

* calibrated using Stuiver and Reimer (1993) and Reimer and others (2004).

Paleoearthquake 4

A fourth colluvial deposit, the lowest unit deposited directly on the faulted fan deposits exposed in the consultant's trench at Whites Creek, is about twice as thick as the overlying colluvial deposits, and thus likely reflects two events (Ramelli and others, 1999a). The deposit is much more clay-rich than the overlying deposits, and Ramelli and others (1999a) thus estimate that PE4 occurred in the late Pleistocene. Alternatively, the clay could have been reworked from the faulted fan deposits and/or the adjacent hillslope, and may thus be a misleading indicator of event age.

Paleoearthquake 4 is older than PE3 (>8,400 ybp), and may be latest Pleistocene.

Fault Slip Rates

The Mt Rose fault zone does not have any well-determined fault slip rates, partly because it is made up of multiple subparallel fault traces and swaths of rates would have to be determined to characterize it, but also because many individual faults have hanging wall complications, such as back-rotation. The only rate that has been approximated is for a single fault trace, single-event interval from Washoe Valley mentioned by Ramelli and dePolo (1997); it is 1.5 m/ky (1.1 – 3.8 m/ky) and is calculated assuming a fault dip of 60º ±10º. They comment:

> "The estimated age of unit 3 determined from radiocarbon dating (about 1700 ka) brackets the two observed events and provides a basis for estimating slip rates, although it is unknown how representative the late Holocene activity is of longer term rates. Based on the relations at trench DCP-1, the late Holocene slip rate is estimated to be between 1.1 and 3.8 mm/yr. The minimum rate is based on one-half the minimum displacement (3.8 m) averaged over the maximum age for unit 3 (1860 yr), and assuming that the two events occurred close to either end of this time range (one interseismic interval of 1760 yr). The maximum rate is based on the maximum displacement (5.8 m) averaged over the minimum age for unit 3 (1530 yr). Considering the range-front morphology and evidence of late Quaternary activity elsewhere along the fault, the higher rate seems unlikely, and a slip rate close to the minimum is tentatively preferred. Using preferred estimates for displacement and age in the same way as the minimum was calculated yields a slip rate of about 1.5 mm/yr."

Earthquake Recurrence Intervals

Timing constraints are available for only a handful of events, so recurrence intervals are estimated from the interseismic intervals between events PE1, PE2, and PE3, assuming the events found in the trenches are representative for the fault zone as a whole and that no earthquakes bypassed the sites (probably a safer assumption for Washoe Valley than

for Whites Creek, considering the highly distributed nature of the fault at the latter site).

Taken at face value, the available age constraints (PE1 = 730 to 930 cal ybp; PE2 = 1,550 to 1,860 cal ybp, and PE3 = 8,420 to 8,590 cal ybp) indicate interseismic intervals of 620 to 1,130 yr (PE1 to PE2) and 6,560 to 7,040 yr (PE2 to PE3), with an average of 3,590 to 8,170 yr. Corrections for deposit/event relations or mean residence time would modify these ranges, but in either case should be relatively small. Similar to the Genoa fault, the two most recent events appear to be clustered in time relative to longer term activity.

Single-Event Displacements

Schilling and Szecsody (1982) excavated three trenches near Whites Creek, including Trench 1 across a young alluvial terrace offset only by the most recent event. In two trenches the fault was characterized by fissures, and offsets ranged from 0.6 to 1.1 m (Schilling and Szecsody, 1982). Subsequent measurements constraining single event displacements come from Davis Creek Park in Washoe Valley and Whites Creek. At Davis Creek Park the offset is measured on a compound fault scarp in a young terrace that is offset by the two most recent events. Ramelli and dePolo (1997) state,

> "Based on VS [vertical separation] of 3.9 ±0.4 m, an estimated fault dip of 60º ±10º, and a surface slope of 2º to 3º, normal displacement (net dip slip) is estimated to be 4.6 m, where net dip slip = VS*(cos(slope)/sin(dip-slope)). The ranges of VS, dip, and slope provide minimum and maximum dip slip estimates of 3.8 m and 5.8 m, respectively. … No constraint on displacement during individual events is available, but assuming similar displacements during the two events suggests displacement per event of between 2 and 2.5 m."

At Whites Creek, the thicknesses of colluvial-wedge deposits provide minimum estimates of vertical offset (Ramelli and others, 1999a). Four colluvial deposits range from ~1 to ~2 m thick, although the thickest deposit could represent two events. The summed thickness of these colluvial deposits is similar to vertical separation at the site, supporting vertical offsets of ~1 m. This is a highly distributed part of the fault system, so these offsets must be minimums for the system as a whole.

Estimates of single-event displacements range from 1 to 2.5 m for the Mt. Rose fault zone. A reasonable preferred value is ~2 m, but measurements come from only three sites and it is uncertain how much distributed deformation should be considered; these estimates are thus unlikely to represent maximum offsets.

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Nevada Quaternary Fault Working Group
FAULT FORM
co-prepared by Alan Ramelli

Peavine Peak fault

Fault Name

Peavine Peak fault
USGS Fault and Fold Database Fault #1644

Introduction

The Peavine Peak fault bounds the steep northeast side of Peavine Peak, the prominent mountain just northwest of Reno. Recent trenching indicates this may be one of the most active faults in Nevada. The fault poses a major threat to the Reno metropolitan area, and several growing suburban communities, including Stead and Silver Knolls, are located on the fault's hanging wall.

Geology of the area has been mapped at 1:24,000 (Bonham and Bingler, 1973; Soeller and Nielson, 1980; Bell and Garside, 1987). Earthquake-hazard "derivative" maps depict the south and north ends of the fault as having Pleistocene activity (Bingler, 1974; Szecsody, 1983), but Bell and Garside (1987) show the central part of the fault to offset Holocene deposits.

Recent trenching revealed that the fault is significantly more active than previously thought, with multiple mid- to late Holocene events (Ramelli and others, 2003). Many details about the fault remain poorly constrained, including the extent of recent ruptures, precise timing of events, and longer-term activity, but the occurrence of multiple recent events and a Holocene slip rate of about 1 m/kyr appear to be fairly definitive. All figures in this report are taken from the Ramelli and others (2003) report.

Location and Length

The northwest-striking, right-normal Peavine Peak fault bounds the northeastern side of Peavine Peak, just northwest of Reno. The south end of the fault is located within about 5 km of downtown Reno. As mapped, the fault has a length of 17 to 20 km, measured from its apparent termination at the western margin of Cold Spring Valley on the north to its approximate intersection with the Carson Range fault system on the south.

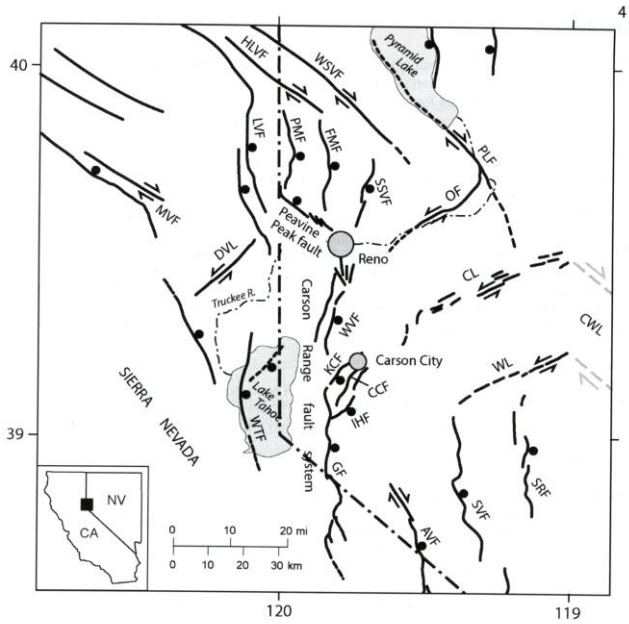


Figure1. Generalized map of Quaternary faults in western Nevada and eastern California. HLVF-Honey Lake fault; WSVF-Warm Spring Valley fault; PLF-Pyramid Lake fault; MVF-Mohawk Valley fault; LVF-Long Valley fault; PMF-Peterson Mountain fault; FMF-Freds Mountain fault; SSVF-Spanish Spring Valley fault; OF-Olinghouse fault; DVL- Dog Valley lineament; WVF-Washoe Valley fault; CL-Carson lineament; KCF-Kings Canyon fault; CCF-Carson City fault; IHF-Indian Hill fault; WL-Wabuska lineament; CWL-projection of Central Walker Lane; WTF-West Tahoe fault; GF- Genoa fault; AVF-Antelope Valley fault; SVF-Smith Valley fault; SRF-Singatse Range fault.

Major Fault and Paleoseismic Investigations

Ramelli, A.R., dePolo, C.M., and Bell, J.W., 2003, Paleoseismic studies of the Peavine Peak fault: Final Technical Report, U.S. Geological Survey National Earthquake Hazard Reduction Program, 14 p.

Summarized information about the Peavine Peak fault, described geomorphic expression, excavated two trenches across the central part of the fault, and constrained recent fault activity.

Ramelli, A.R., Bell, J.B., and dePolo, C.M., 2004, Peavine Peak fault: another piece of the Walker Lane puzzle: Western States Seismic Policy Council, Basin and Range Province Seismic Hazards Summit II, Program and Abstracts, p. 126.

Reported summary of dates from the trenching study.

Geomorphic Expression

The central part of the Peavine Peak fault (Peavine Peak section) forms a steep range front with fault facets and large fault scarps in alluvium. The fault also has side-hill scarps and benches, small fault scarps, springs along the fault, and aligned drainages. The Dry Hills Summit section extends through a widespread landslide area that largely masks the fault's expression. The Cold Spring Valley section bounds a low ridge with a barely discernable steepened midslope, while the Lemmon/Panther Valley section forms subdued scarps and springs along several left-stepping, en echelon faults.

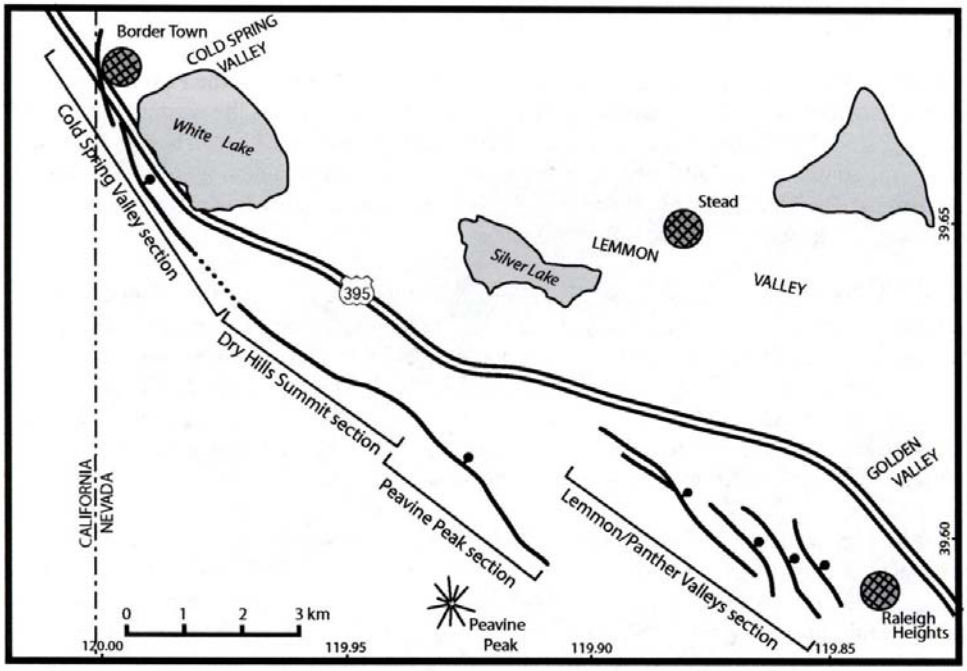


Figure 4. Geomorphic sections of the Peavine Peak fault

Structural Description

The Peavine Peak fault overall strikes ~ N43ºW, but bends more northerly at its northwestern end. The most prominent part of the fault (Peavine Peak section) is a frontal fault generally located at the bedrock/alluvium contact. The northern and southern ends of the fault distribute into multiple fault strands. The Peavine Peak fault truncates several north-striking, down-to-the-east faults, including the Peterson Mt. and Freds Mt. faults, and interaction with these faults may cause changes in activity along the Peavine Peak fault.

There are well-developed geomorphic features, such as facets and a steep range front, indicating normal displacement along the Peavine Peak fault, but the fault strikes parallel to right-lateral faults of the Walker Lane, it has left-stepping patterns, and there is a pull-apart basin at its north end (Cold Spring Valley), all consistent with a right-lateral component.

The fault structure exposed in the trenches supports a lateral component (Ramelli and others, 2003). The exposed part of the fault zone (upper 3-4 m) can be described as a flower structure with a central zone and two flanking faults. The main fault and a mountain-ward fault are both down-to-the-northeast, while a basin-ward fault has a small down-to-the-southwest offset. The main fault zone is near vertical (dipping steeply southwest). Elongate cobbles within the fault zone had an average orientation with an eastward plunge, indicating a right-lateral component. Ramelli (2007, written commun.) measured the orientation of the clasts and estimates a ratio of ~2:1, normal to right-lateral displacement.

One might expect geomorphic indicators of a lateral component (e.g., deflected drainages), but such features aren't obvious. Two possible reasons for this are: 1) the dominant vertical component causes overwhelming depositional change across the fault; and 2) the area receives more precipitation than is average for the region, and thus it has a dense brush cover and alluvial surfaces are largely smoothed.

Earthquake History

Trenching indicates the occurrence of at least four and possibly five Holocene earthquakes, all offsetting a mid-Holocene fan deposit (Ramelli and others, 2003). Bulk radiocarbon dating provided mixed results, with several of the dates out of stratigraphic order, but they are nonetheless generally consistent with soil development in the fan deposit (dates are shown on the trench log at the end of the report).

Trench 1 exposed offset fan deposits of sandy cobble and pebble gravels with some moderate stratification and local sorting that allowed delineation of bedding planes and distinction from the more jumbled scarp colluvium and fissure fill deposits. Colluvial deposits are mostly made up of fallen and eroded fan deposits. The fan has a dark cumulate mollic A horizon overlying a weak cambic B horizon, but no other indicators of soil formation; this is consistent with a mid-Holocene age for this soil.

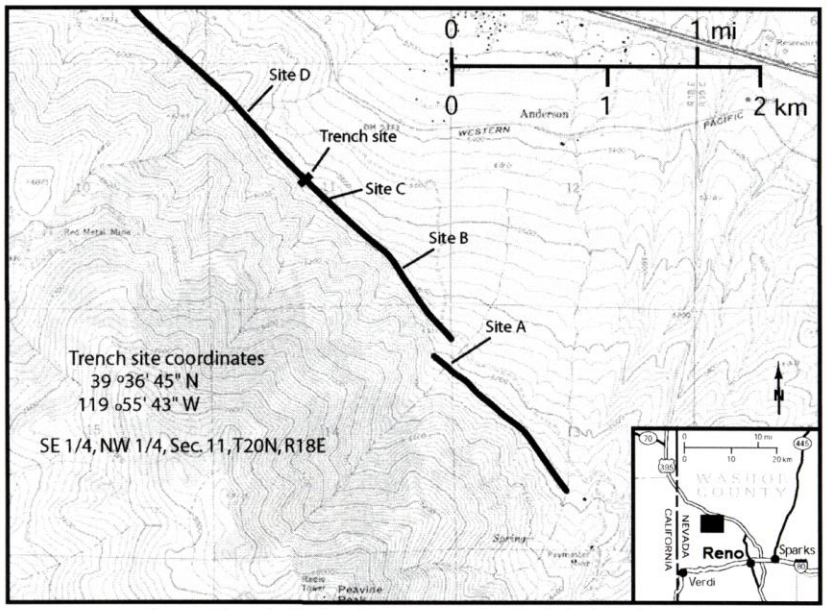


Figure 6. Trench site location map, Peavine Peak fault project

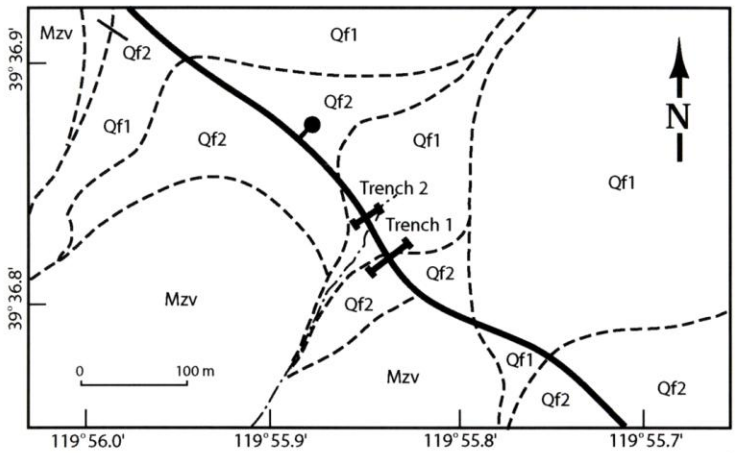
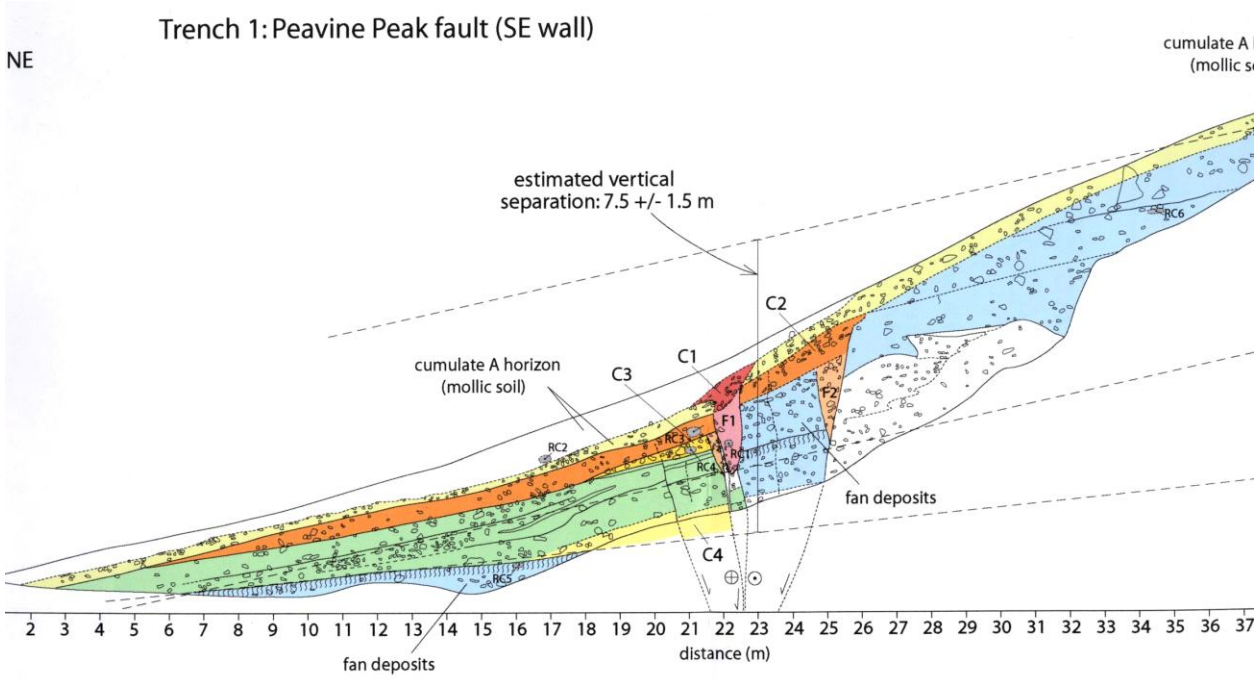
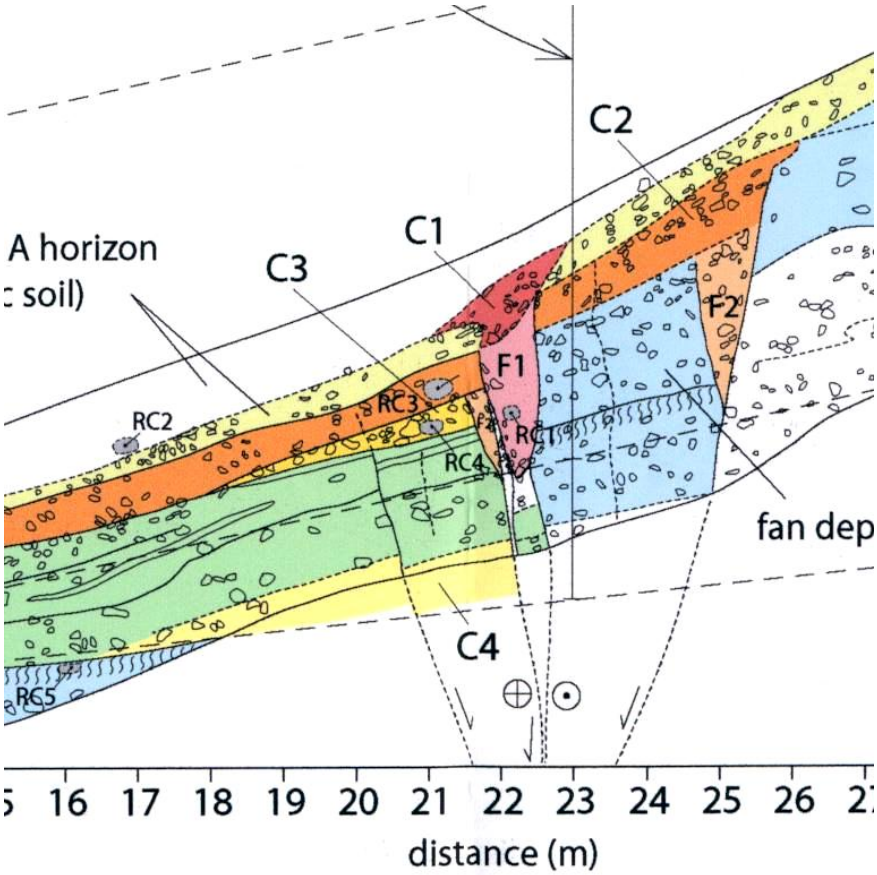


Figure 7. Generalized surficial geology map of the Peavine trench site. Qf1- mid- to late Holocene alluvium; Qf2- early to mid Holocene alluvium; Mzv- Mesozoic metavolcanics. Qf1 contacts are extended downslope to show approximate alluvial-fan boundaries.



Fan deposits are colored blue, colluvial deposits are labeled "C1, C2" and so forth, fissure fill deposits are labeled "F1" and "F2"; the numbers correlate with paleoevent numbers. The fault is a splaying upwards flower structure. No vertical exaggeration. From Ramelli and others (2003)



Radiocarbon dates (ybp):

RC1	6,220 ±100 ^{14}C
RC2	2,430 ±70 ^{14}C
RC3	5,540 ±100 ^{14}C
RC4	1,710 ±100 ^{14}C
RC5	2,330 ±130 ^{14}C
RC6	590 ±100 ^{14}C

The evidence for earthquakes from Trench 1 (Ramelli and others, 2003):

Paleoearthquake 1

Paleoearthquake 1 formed a fissure about 0.7 m wide and 2 m deep along the central (main) fault trace, the only fault trace that moved during this event. The fissure is filled with dark organic-rich soil material, and is capped by a small post-event colluvial wedge (C1). Vertical offset during PE1 is estimated at about 0.5 m.

Paleoearthquake 2

Paleoearthquake 2 involved both the main fault and the western (mountain-ward) fault, with a combined vertical offset of more than 1 m. PE2 formed fissures along both of these fault traces (the one along the central trace being about 0.3 m wide and 1 m deep along, and the one along the western trace being about 0.8 m wide and 2 m deep). PE2 also resulted in deposition of a cobbly colluvial wedge (C2) that extended from the western fault to the toe of the scarp.

Paleoearthquake 3

Paleoearthquake 3 is indicated by a small scarp-derived colluvial wedge (C3) that is cut by the PE2 fissure along the main fault, while capping a small fault offset (PE3) in the underlying deposits. PE3 is estimated to have a vertical offset of more than 0.5 m (based on wedge thickness), but less than occurred in PE2.

Earlier Events (PE4 and PE5?)

Scarp-derived colluvium barely exposed in the bottom of the trench (C4) indicates at least one additional event. From the amount of offset indicated (~2 m), two events of PE2 size would be required to form the >1 m thick deposit.

Fault Slip Rates

Trenching along the central part of the Peavine Peak fault revealed four or five events, with a cumulative vertical separation of ~7 m; the fault zone appears to be subvertical, so vertical separation should closely approximate vertical displacement. Aligned clasts from the fault zone suggest an approximate slip ratio of 2:1 vertical to horizontal, indicating a net slip of ~8 m. Six radiocarbon dates are out of stratigraphic order, but the older dates (5,540 ±100 ^{14}C ybp and 6,220 ±100 ^{14}C ybp) are consistent with the cambic soil formed in the fan. The dated material is therefore assumed to be reworked from the faulted fan deposits and to bracket the 8 m offset. These data indicate a slip rate of slightly over 1 m/ky, but there are large uncertainties in both offsets and ages, so the

estimated rate is rounded off to 1 m/ky (Ramelli, 2007, written commun.). Calendar corrected ages for the two samples are 6,020 to 6,600 cal ybp, and 6,810 to 7,410 cal ybp, respectively (calendar corrected using Stuiver and Reimer, 1993 and Reimer and others, 2004).

Earthquake Recurrence Intervals

Averaging 4 or 5 events over the oldest corrected age range indicates a mid- to late Holocene earthquake recurrence interval of 1,360 to 1,850 yr.

Earthquake Segmentation

Earthquake-hazard maps depict the south and north ends of the fault as pre-Holocene (Bingler, 1974; Szecsody, 1983). The two ends of the fault have much more subdued expression than the central part, suggesting this may be true, but other earthquake-hazard maps of similar vintage in the Reno area depict many faults as being older than subsequent studies have demonstrated. Although activity along the entire zone remains unresolved, we currently consider it more likely that displacement dies off toward the ends, rather than the fault being segmented into uncommonly short ruptures.

Although segmented with respect to geomorphic expression, no subdivision of the Peavine Peak fault is proposed for consideration of potential earthquake segments. The Peavine Peak fault is interpreted to be a single earthquake segment, with a prominent central portion and less prominent ends. A single segment model, with a length of 17 to 20 km, is consistent with displacements of >1 m.

Single-Event Displacements

Based on 7.5 +/- 1.5 m of vertical offset, and 4 or 5 events, average single-event displacements (vertical only) are estimated to be 1.2-2.25 m. Including the apparent lateral component increases this estimate to 1.4-2.6 m.

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Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Bertrand, C. J. H., Blackwell, P. G., Buck, C. E., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Hogg, A. G., Hughen, K. A., Kromer, B., McCormac, F. G., Manning, S. W., Ramsey, C. B., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver, M., Talamo, S., Taylor, F. W., van der Plicht, J., and Weyhenmeyer, C. E., 2004, IntCal04 Terrestrial radiocarbon age calibration, 26-0 ka BP: Radiocarbon, v. 46, p. 1029-1058.

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Nevada Quaternary Fault Working Group **<u>Olinghouse fault zone</u>**
FAULT FORM

Fault Name

Olinghouse fault zone
USGS Fault and Fold Database Fault # 1668

Location and Length

The Olinghouse fault is located about 15 km east of Reno-Sparks urban area, and about 10 km northwest of Fernley, a rapidly growing community. The fault extends from near Tracy in the Truckee River canyon to the eastern side of Dodge Flat in west-central Nevada, a length of approximately 25 km (Briggs and Wesnousky, 2005). The minimum distance for a continuous fault zone is ~20 km (from northwest of Clark to east of White Hill). The maximum distance is about 27 km (from near Patrick on the west to an intersection with the Pyramid Lake fault zone. All of these are end-to-end distances.

There is a possible southwestward extension of this fault zone, which has not been adequately explored; this is a possible continuation to the south along the northwestern flank of Clark Mountain, and a possible connection to the Northern Virginia Range fault, that would nearly double the length of the Olinghouse fault zone.

From Sanders and Slemmons (1996)

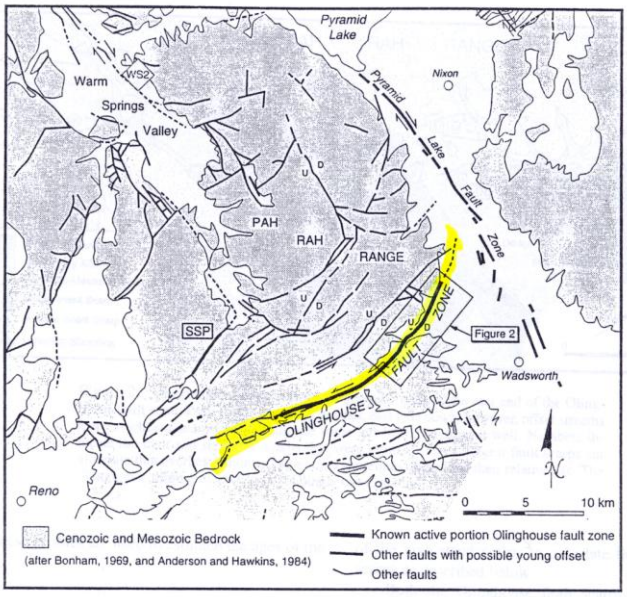

Figure 1. Location of the Olinghouse fault zone and general geology. SSP: Spanish Springs Peak. WS2 is the location of a shoreline scarp profile listed in Table 1.

Major Fault and Paleoseismic Investigations along the Olinghouse Fault Zone (chronologically presented)

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Sanders, C.O. and Slemmons, D.B., 1996, Geomorphic evidence for Holocene earthquakes in the Olinghouse fault zone, western Nevada: Bulletin of the Seismological Society of America, v. 86, p. 1784-1792.

Briggs, R.W. and Wesnousky, S.G., 2005, Late Pleistocene and Holocene paleoearthquake activity of the Olinghouse fault zone, Nevada: Bulletin of the Seismological Society of America, v. 95, p. 1301-1313.

Geomorphic Expression

The Olinghouse fault can be relatively easily traced across the landscape based on its geomorphic expression, except where it is hidden by recent alluvium (Sanders and Slemmons, 1979). A geomorphic strip map of the fault zone by Briggs and Wesnousky (2005) is shown in figure 3. Geomorphic expression includes fault scarps, uphill-facing fault scarps, vegetation lineaments, sidehill benches, shutter ridges, sag ponds, ridge saddles, offset stream channels, offset stone-stripes, offset debris-flow levees, enclosed rhombohedral and wedge-shaped depressions, and echelon-stepping fractures (Sanders and Slemmons, 1979; Briggs and Wesnousky, 2005).

Structural Description

The Olinghouse fault zone is broad in places, as much as almost 1 km wide, and a fairly discrete fault in places, particularly along its eastern reach. It is conjugate with, and intersects at its north end of, the Pyramid Lake fault zone. The Olinghouse fault zone is arcuate in shape, changing strike from ~N60ºE near Tracy to ~ N30ºE along its eastern end, near the Pyramid Lake fault zone. The fault zone is located along the base of the Pah Rah Range, and along small outboard hills that flank the range. The Olinghouse fault zone is left-lateral strike-slip based on offset debris levees and its overall orientation (Sanders and Slemmons, 1979; Briggs and Wesnousky, 2005), although multiple orientations of slickenlines have been found on bedrock surfaces by Cashman and Ellis (1994), indicating the zone may undergo different senses of displacement with different events.

The fault zone has been mapped at a scale of 1:24,000 along its eastern half (Bell and others, 2005; Garside and Bonham, 2006). Sanders and Slemmons (1979) and Briggs and Wesnousky (2005) also mapped out the Olinghouse fault zone for their fault studies.

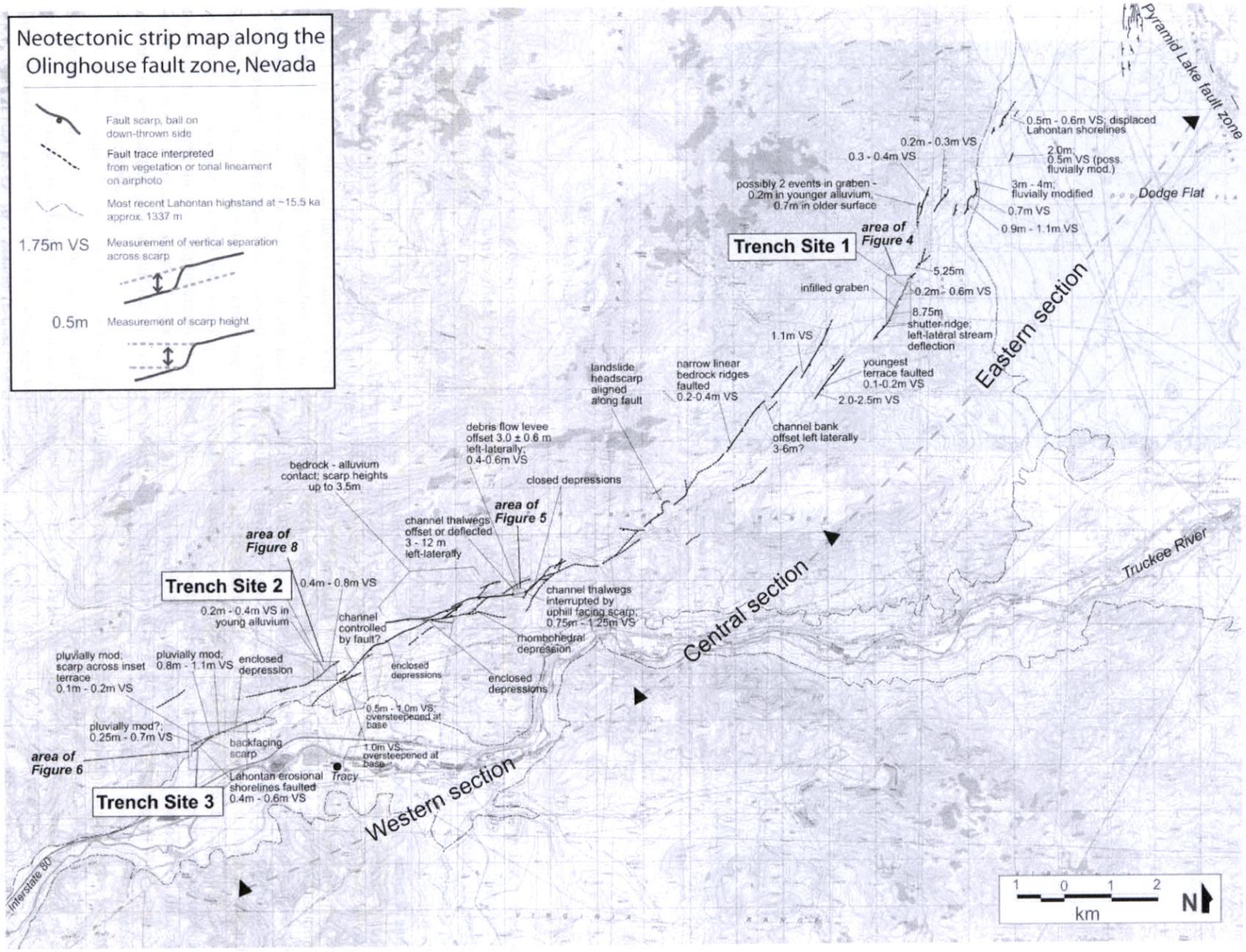

Figure 3. Strip map of the most recently active fault trace and associated features along Olinghouse fault zone.

From Briggs and Wesnousky (2005)

The Olinghouse fault zone is divided into three geologically distinct sections by Briggs and Wesnousky (2005), as shown on their figure 3. The most diagnostic feature of these sections in the dominance of the fault being located in bedrock and lacking fault scarps in young alluvium along the central section, whereas there are Quaternary alluvial tectonogeomorphic features on the western and eastern sections.

Earthquake History

Historical Earthquake(?)

A historical earthquake occurring in 1869, known for a while as the "Olinghouse earthquake," was attributed to the Olinghouse fault (e.g., Sanders and Slemmons, 1979), but this does not seem likely based on earthquake intensity patterns from that earthquake (c.f., Toppozada and others, 1981; dePolo and others, 2001). The only candidate earthquake that may have ruptured the Olinghouse road in the 1860s is the May 15, 1860 earthquake (dePolo and others, 2001). This event appears to have occurred in the Pah Rah Range – southern Pyramid Lake region, but there is little direct information about this event. Sanders and Slemmons (1996) carefully looked in all possible locations on the Olinghouse mining road and in none of the locations did they find any possible candidates for a historical earthquake. Sanders and Slemmons (1996) concluded that either: 1) neither the 1860 nor 1869 earthquakes occurred along this reach of the Olinghouse fault, 2) one of these earthquakes occurred along this reach, but did not have enough of a normal component to be preserved (just cracking), or 3) one of these earthquakes occurred along this reach but had a small amount of strike-slip displacement and thus is undetectable today.

Paleoearthquakes

The dating of paleoearthquakes has been accomplished trenching studies (Briggs and Wesnousky, 2005). Some scarp morphology studies have also been conducted by Sanders and Slemmons (1996).

Scarp Morphology Studies

Sanders and Slemmons (1996) used scarp degradation studies of single event and compound scarps to estimate the time of the last offset of the eastern part of the Olinghouse fault zone. They took advantage of latest Pleistocene Lake Lahontan shore lines occurring within a few kilometers of the fault scarps that have estimated ages of ~15.5 ka to calibrate a local diffusion coefficient for their scarp modeling. Sanders and Slemmons (1996) concluded that the age of the most recent event along this part of the fault is 4.5 ±2 ka. In their analysis of composite scarps they conclude that two or three large earthquakes have occurred since about 21 ka, and estimate that the recurrence

interval of the Olinghouse fault zone is 8 to 16 ky.

Trenching Studies

Briggs and Wesnousky (2005) trenched the Olinghouse fault zone in three places, one trench along the eastern part and two trenches along the western part. They concluded that there are different earthquake histories for the eastern versus western parts of the fault based on these trenching studies, with the eastern part being more active. Each trench site and the results will be briefly reviewed, and the overall paleoearthquake history of the fault zone will be discussed at the end.

Trench 1 (eastern part of the Olinghouse fault zone)

Trench 1 was placed across an east-facing fault scarp with 60 cm of vertical separation of the surface (Briggs and Wesnousky, 2005); this part of the fault strikes ~N35ºE. The trench exposed an asymmetric flower structure with faults near the toe and upper parts of the fault scarp (see Trench 1 log). Briggs and Wesnousky (2005) favor a two earthquake interpretation of the trench exposure, but allow an uncertainty of a third event to explain an apparent thickening of unit 4. Although measured vertical offsets are reported by Briggs and Wesnousky (2005), they readily advocated that the Olinghouse fault zone is a dominantly strike-slip fault with potential coseismic offsets of as much as 3 m.

Evidence for the most recent event at Trench 1 is offset of unit 5 along several faults, a sheared fissure fill that crosses unit 5, and offset of scarp-derived colluvium from the penultimate event (important for superposition with the prior event); unit 5 was offset vertically about 30 cm by the
most recent event (Briggs and Wesnousky, 2005).

Evidence for the penultimate event at Trench 1 includes offset of units 1-4, and the formation of scarp-derived colluvium (unit C1). Units below colluvium C1 are offset vertically 70 to 90 cm, and subtracting out the 30 cm from the most recent event leaves 40 to 60 cm of vertical offset for earlier events. In Briggs and Wesnousky's (2005) interpretation all of this displacement occurred during the penultimate event.

Unit 4 shows some apparent thickening across the fault zone, which could be interpreted as evidence that an event occurred before the penultimate event. Briggs and Wesnousky (2005) did not favor this interpretation because: 1) thickness differences in unit 4 are probably due to erosion during deposition of unit 5 rather than deposition of unit 4 against a scarp, 2) the offset of the base of unit 4 (70 cm) is slightly smaller than offsets of unit 2 and 3 (85-90 cm), but because the fault is predominantly strike-slip, and beds are not horizontal, so these differences are not diagnostic of a separate event, 3) no scarp-derived colluvium is observed that would be associated with a third event. Briggs and Wesnousky (2005) concluded, "Taken together, the observations suggest a third earthquake preserved in Trench 1 is possible but unlikely." I might add that unit 4 has a

uniform thickness on the east side (it does not appear to fill any local tectonic depression and that a slight reverse drag on the east side shows highly parallel and equally drug contacts between units 2 and 3, 3 and 4, and 4 and 5, which also does not support a third event.

A recent earthquake history is complete at Trench 1, beginning with the Mazama ash, 7,627 ±150 cal. ybp. (Briggs and Wesnousky, 2005). The maximum age of unit 3 (a pre-faulting unit) is 3,360 ±190 cal. ybp, based on an AMS radiocarbon date of detrital charcoal (sample Olig C-1); two to three events are after this date (Briggs and Wesnousky, 2005). The age of the most recent event is further constrained to being younger than a detrital charcoal sample from colluvium C1 dated at 2,980 ±190 cal. ybp (sample Oling C-2).

Trench 2

Trench 2 was excavated across an ~40-cm-high fault scarp in intermittent channel deposits (Briggs and Wesnousky, 2005). The site was chosen to investigate the most recent event along the western part of the Olinghouse fault zone; there is a second, subparallel fault trace of the zone that was not trenched. Trench 2 exposed poorly sorted fluvial sands and gravels and a small amount of scarp-derived colluvium, but no discrete fault. The fault was marked by a broad 1- to 2-m-wide zone of disrupted bedding and poorly developed shear fabric (Briggs and Wesnousky, 2005). Near the base of the trench there is little apparent vertical offset, whereas there was about 40 cm of vertical displacement of the ground surface (Briggs and Wesnousky, 2005). Briggs and Wesnousky (2005) attributed this difference in offset to strike-slip faulting.

Only the most recent event along the western part of the fault zone was exposed in Trench 2, the timing of which is constrained by a sample of detrital charcoal collected from offset deposits (unit 3), and radiocarbon dated at 1935 ±70 cal. ybp (sample Tracy C-1); this is a maximum date for the deposit and the paleoearthquake.

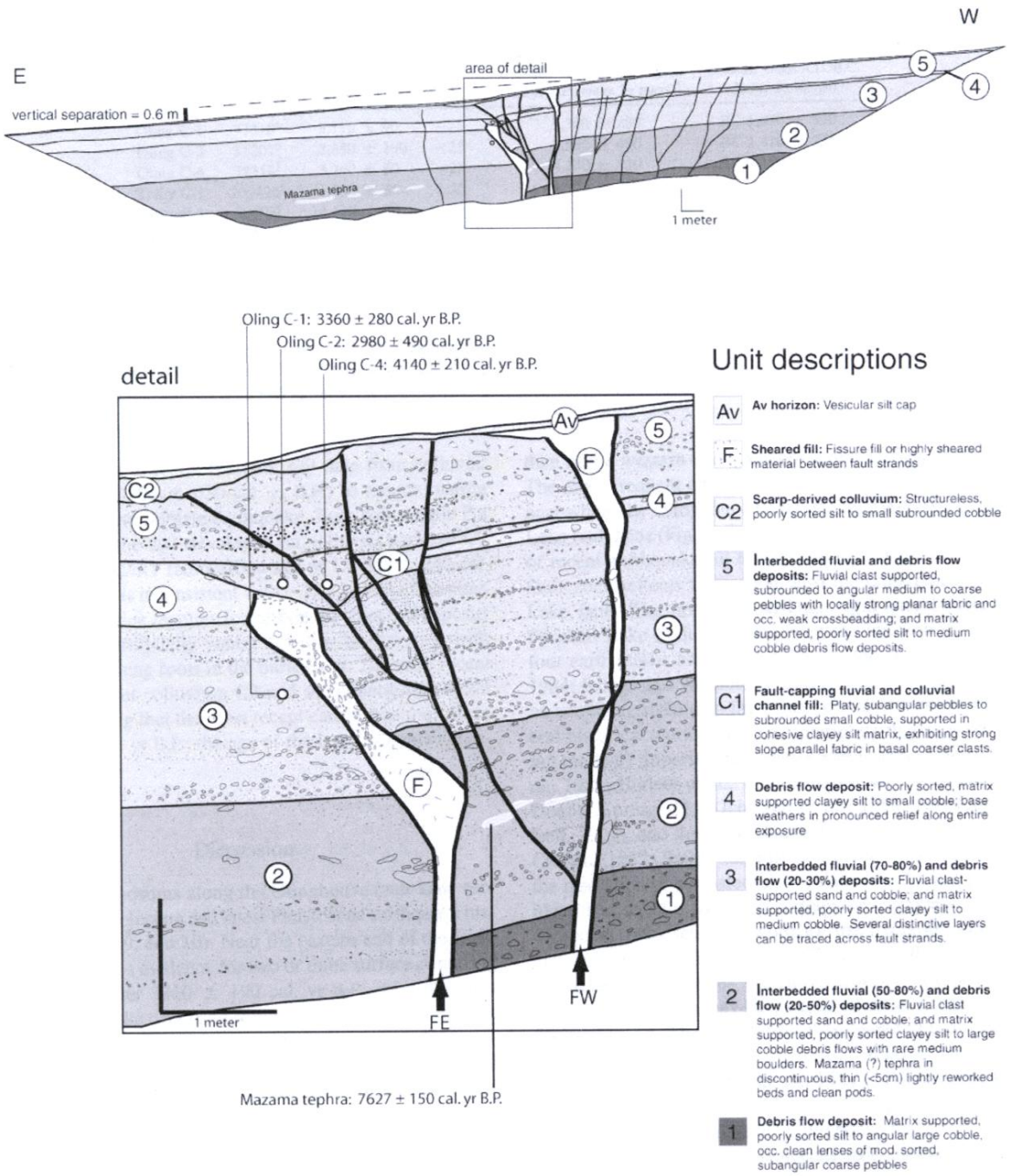

Figure 7. Trench log, trench 1. See Figures 2, 3, and 4 for location.

Trench 1 - from Briggs and Wesnousky (2005)

Trench 3

Trench 3 was dug across a uphill-facing fault scarp with 15 to 20 cm of vertical separation formed on an alluvial fan in the western part of the zone (Briggs and Wesnousky, 2005). Briggs and Wesnousky (2005) noted that recessional shorelines from latest Pleistocene Lake Lahontan are also formed on the fan surface and are offset by the fault, indicating movement in the last ~15.5 ky. Briggs and Wesnousky (2005) also noted that the trench is located near the end of a mapped fault trace, "raising the possibility that the trenched deposits do not fully record surface-rupturing earthquakes along this section of the fault." Trench 3 exposes debris flow deposits with interbedded channel gravels, fluvial gravels, and colluvial packages. Two faults are recognized, Faults FN and FS (FN -fault north and FS -fault south).

Three paleoearthquakes are identified in Trench 3 (Briggs and Wesnousky, 2005). The youngest event, T3PE1 (this is the youngest paleoearthquake in Trench 3, but not necessarily of the fault zone), comes close to the surface and offsets all the deposits in the trench. The colluvial deposit that is related to the prior earthquake along Fault FS is offset, and the apparent throw is different from earlier indicating strike-slip displacement (Briggs and Wesnousky, 2005). Along Fault FN, there was offset of the uppermost deposit and a possible wedge-shaped colluvial deposit was formed (unit C3?). The youngest event offsets shoreline features of latest Pleistocene Lake Lahontan, and thus is less than ~15.5 ka. (These are recessional shoreline features that are relatively high in elevation and are near the high-stand shoreline; they are likely very close in age to that of the high shoreline.)

Evidence Paleoearthquake 2 in Trench 3 (T3PE2) is along Fault FS and consists of offset of a colluvial deposit related to the prior earthquake (unit C1) and the development of colluvial deposit, unit C2. The age of T3PE2 is bracketed by bulk radiocarbon dates of the upper parts of colluvial deposits C1 and C2. These have radiocarbon dates of 19,800 ±630 cal. ybp (sample Pat-Soil 1) and 12,890 ±240 cal. ybp, respectively (sample Pat-Soil 2; Briggs and Wesnousky, 2005). Unfortunately, the age on unit C2 is younger than the ~15.5 ka age of the shorelines formed on the deposit. Briggs and Wesnousky (2005) explain this younger date as likely contaminated by younger material and adopt the 15.5 ka as the bounding age between T3PE2 and T3PE1. Available data brackets T3PE2 as between 19,800 ±630 ybp and 15.5 ka.

The oldest event, T3PE3, offsets Units 1b and 2 along Fault FS, and formed the colluvial deposit C1. This event is older than the radiocarbon date taken from near the top of colluvium C1, 19,800 ±630 cal. ybp.

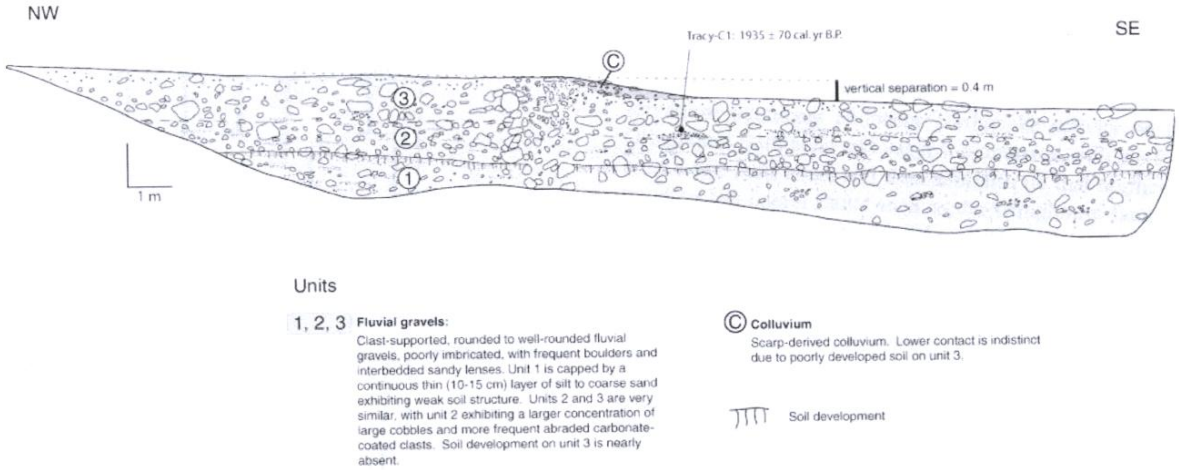

Figure 9. Trench log, trench 2. See Figures 2, 3, and 8 for location.

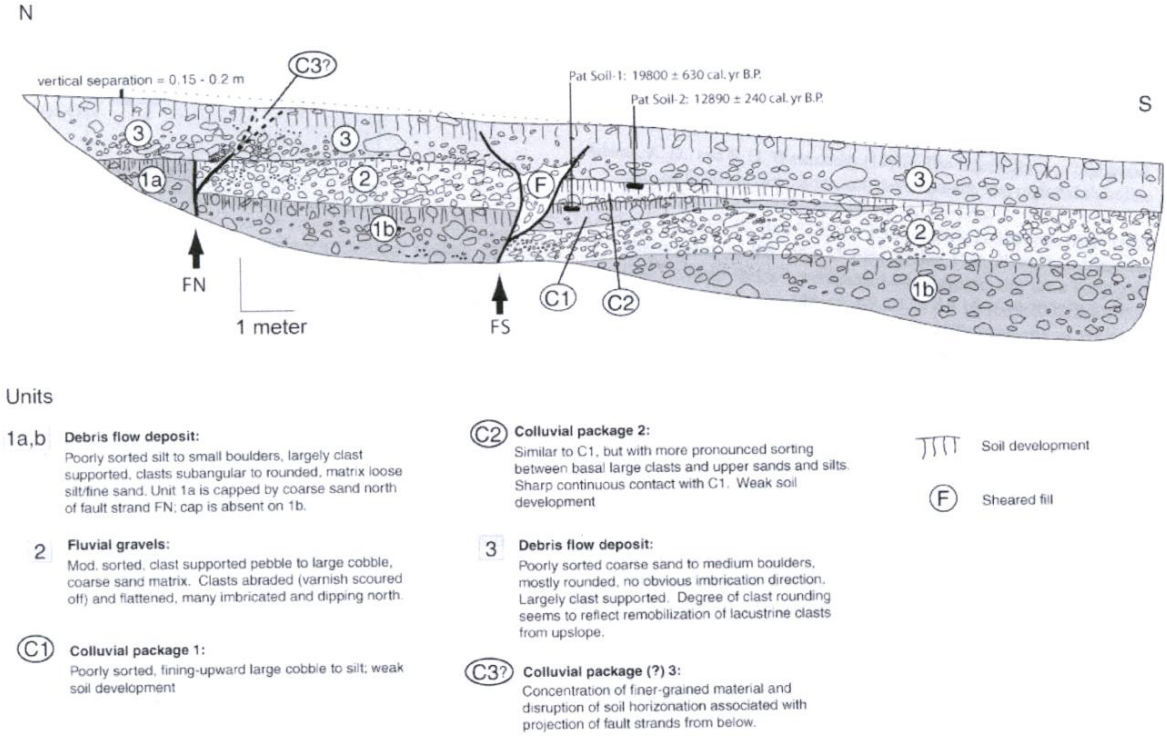

Figure 10. Trench log, trench 3. See Figures 2, 3, and 6 for location.

Trench 2 & 3 from Briggs and Wesnousky (2005)

Summary of Paleoearthquakes along the Olinghouse fault zone

Figure 11 from Briggs and Wesnousky (2005) summarizes the paleoseismic information found in the trenches and their paleoearthquake model for the Pyramid Lake fault zone.

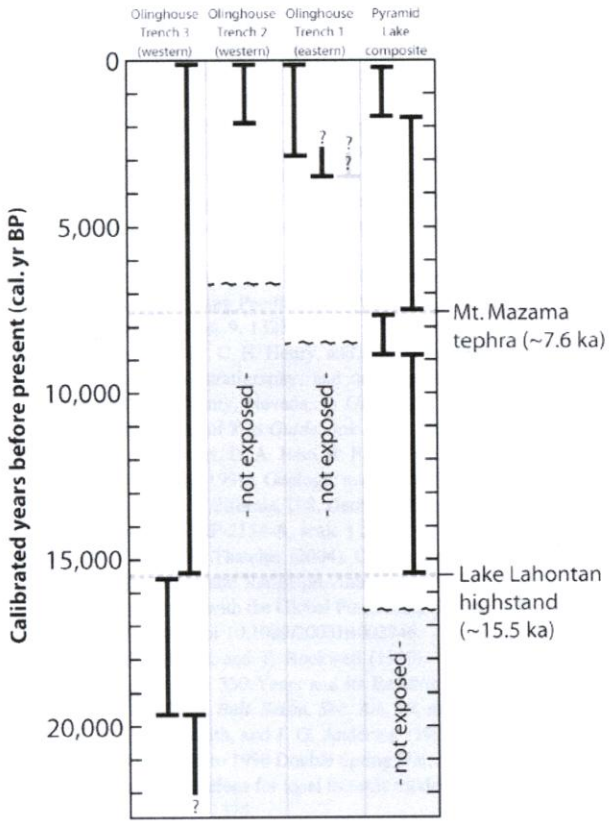

Figure 11. Summary of paleoearthquake timing of Olinghouse and Pyramid Lake fault zone trench exposures. Dark bars represent time interval during which each earthquake may have occurred. Grey line in Trench 1 is possible 3rd earthquake. Pyramid Lake fault zone composite record from Briggs and Wesnousky (2004).

There appears to have been a relatively young event along the entire length of the Olinghouse fault zone. This earthquake (PE1) is less than about 2000 years old along the western end and ruptured to near the surface. The fault is buried by very young sediments along the eastern end. This event had surface offsets of as much as 3 m, thus the entire fault zone likely was ruptured. Available information indicates that the prior event (PE2) that ruptured the entire fault zone was prior to the Lake Lahontan high stand, in the range of 20,430 to 15,500 ybp.

As discussed by Briggs and Wesnousky (2005) the eastern end of the fault, where it approaches the Pyramid Lake fault zone, has evidence for an additional one and possibly

two post-Mazama ash events. Briggs and Wesnousky (2005) speculated that the higher activity of the Pyramid Lake fault zone occasionally causes triggered slip along the eastern end of the Olinghouse fault zone, leading to this increase in activity.

Fault Slip Rates

No estimates of the slip rate of the Olinghouse fault have been presented in the literature. There is enough information to create a single-event slip rate, however, although it is difficult to know how representative this value is of the overall rate.

The most recent event along the Olinghouse fault zone had a left-lateral offset of 2.4 to 3.6 m (Sanders and Slemmons, 1979; Briggs and Wesnousky, 2005). There is a smaller vertical offset of 0.5 m, but this is inconsequential in the slip rate estimate (i.e., considering a net displacement).

The accumulation or strain build-up period before PE1 is estimated by subtracting the time since PE1 from the age of PE2. Paleoearthquake 1 occurred after 1,935 ±70 cal. ybp, or <1,870 to <2,010 ybp (Briggs and Wesnousky, 2005) and is older than at least 90 years prior to 1950 (the radiocarbon reference year). The age of PE2 is between 19,800 ±630 cal. ybp (Briggs and Wesnousky, 2005) and the age of the most recent high stand of Lake Lahonton, 15,500 (+450, -380) cal. ybp (Adams and Wesnousky, 1998). These constraints place PE2 between 19,170 to 20,430 ybp and 15,120 to 15,950 ybp. The maximum range of PE1's accumulation period using these values is 13,110 to 20,340 years. Dividing 3.6 m by 13.1 ky gives the maximum slip rate estimate or 0.27 m/ky and dividing 2.4 m by 20.3 ky gives the minimum rate of 0.12 m/ky.

The slip rate calculated for the most recent event along the Olinghouse fault zone is 0.1 to 0.3 m/ky; it is uncertain how representative this slip rate is in space and time.

Earthquake Recurrence Intervals

Only one earthquake interseismic interval is available to view, and it is uncertain how representative it. The interval is between PE2 and PE1 for the Olinghouse fault zone.

The interseismic interval between PE2 and PE1 can be estimated by subtracting the time since PE1 from the age of PE2. Paleoearthquake 1 occurred after 1,935 ±70 cal. ybp, or <1,870 to <2,010 ybp (Briggs and Wesnousky, 2005) and is older than at least 90 years prior to the radiocarbon reference year, 1950 (PE1 was no later than 1860). The age of PE2 is between 19,800 ±630 cal. ybp (Briggs and Wesnousky, 2005) and the age of the most recent high stand of Lake Lahonton, 15,500 (+450, -380) cal. ybp (calendar corrected from Adams and Wesnousky, 1998). These constraints place PE2 between 19,170 to 20,430 ybp and 15,120 to 15,950 ybp. The maximum range of the interseismic interval between PE2 and PE1 using these values is 13,110 to 20,340 years.

Evidence from Trench 1 indicates a second and possible third event that might have been triggered events limited to the eastern part of the Olinghouse fault zone since 3,360 ±190

ybp. This adds a chance of having additional events along the eastern part of the fault zone, but this is difficult to quantify given the data at hand. Briggs (2007, email) thinks the alternative, that Trench 1 has the record of the events on the Olinghouse fault zone and the exploration on the western end did not capture the additional events (possible rupture on unexplored subparallel fault traces or subsurface rupture along the west end), should also be considered. Because this additional event(s) would be constrained as being less that 3,360 ±190 ybp, a minimum interseismic interval of 1,000 to 2,000 years is implied for this alternative model, as well as variability in this interval from event to event.

Thus the range of possible recurrence intervals for the Olinghouse fault zone is ~1,000 to ~20,000 years, given current information.

Earthquake Segmentation

No segmentation of the Olinghouse fault zone has been proposed. The most recent event had offsets that are about 2 to 3 m, indicating the entire 25-km fault zone likely ruptures during major earthquakes. An eastern subsegment might be considered to model possible triggered slip from the Pyramid Lake fault zone.

Single-Event Displacements

Sanders and Slemmons (1979) measured offset drainage channels and stone stripes in the western part of the Olinghouse fault zone as being offset left-laterally by 3.65 m. Briggs and Wesnousky (2005) also measured left-laterally offset features from the approximate same area. They made a topographic map of an offset debris flow levee and channel pair. The levee has 3.0 ±0.6 m of left-lateral offset, and 0.5 ±0.1 m vertical offset, and it thought to be displacement from the most recent event along this part of the fault (Briggs and Wesnousky, 2005); the channel thalweg is offset 2.75 ±0.75 m laterally.

Thus, a single event displacement of 2.75 - 3.7 m left lateral, and 0.5 m vertical occurred during the most recent event. Although this is a fairly large displacement for the overall length of the fault, two independent research groups have come to similar conclusions.

Additional References

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Bell, J.W., Garside, L.J., and House, P.K., 2005, Geologic map of the Wadsworth Quadrangle, Washoe County, Nevada: Nevada Bureau of Mines and Geology Map 153, scale 1:24,000.

Briggs, R.W. and Wesnousky, S.G., 2004, Late Pleistocene fault slip rate, earthquake recurrence, and recency of slip along the Pyramid Lake fault zone, northern Walker Lane, United States: Journal of Geophysical Research, v. 109, B8, B08402, doi 10.1029/2003JB002717.

Cashman, P.H. and Ellis, M.A., Fault interaction may generate multiple slip vectors on a single fault surface: Geology, v. 22, p. 1123-1126.

dePolo, C.M., Ramelli, A.R., Hess, R.H., and Anderson, J.G., 2001, Reevaluation of pre-1900 earthquakes in western Nevada: Nevada Bureau of Mines and Geology Open-File Report 01-2, 175 p.

Garside, L.J., 2006, Geologic map of the Olinghouse Quadrangle, Washoe County, Nevada: Nevada Bureau of Mines and Geology Map 157, scale 1:24,000.

Toppozada, T.R., Real, C.R., Parke, D.L., 1981, Preparation of isoseismal maps and summaries of reported effects for pre-1900 California earthquakes: California Division of Mines and Geology Open-File Report 81-11 SAC, 182 p.

Fault Name

Pyramid Lake fault zone
USGS Fault and Fold Database # 1669

Introduction

The Pyramid Lake fault zone is one of the most active late Quaternary faults in Nevada, and poses a high earthquake hazard to the Pyramid Indian Reservation and the growing community of Fernley, Nevada. Fernley is one of the most rapidly growing areas in the state and has the potential to increase and expand in surprising ways because it is located along Interstate 80 (and a national east-west railroad line) at an intersection with a major north-south highway (HWY 95) and a cut-off to a major east-west highway (HWY 50).

Location and Length

The Pyramid Lake fault zone is located in the northern Walker Lane in western Nevada; it lies under, and south of, its namesake Pyramid Lake. The fault zone is generally located in a mid-valley position, although is northern portion is near the base of the Pah Rah Range (on the western side of the fault).

The length of the Pyramid Lake fault zone is uncertain because the ends are undefined. The southern end can either be taken at the southern end of the Holocene activity or at the southern end of Quaternary faulting. The distributed nature of the southern end is partly responsible for the uncertainty of the end. The Pyramid Lake fault zone might extend to a truncation with the northeast-trending Carson lineament, but faults have not been mapped along the southernmost reach of this extension. The northern extension of the fault zone is under water, and more detailed imaging studies need to be conducted before we can understand the true extent of the zone under Pyramid Lake.

A minimum Holocene end-to-end length of the fault zone is ~38 km, taken from Pyramid Lake southward to the end of Holocene activity (Bell, 1984; Briggs and Wesnousky, 2004 – fig. 5). A likely Holocene length includes a 20-km extension under Pyramid Lake (see below), for a total of ~58 km.

For a maximum length, ~13 km can be added to the south to get to the Carson lineament, and Briggs and Wesnousky (2004) commented that the fault zone continues to the north, at most, 40 km under Pyramid Lake. Examination of the imagery of the floor of Pyramid Lake, and considering the extend of the section of the southwestern shore of Pyramid Lake that is parallel to the fault zone, a maximum length of 20 km seems more likely.

Strain from the north part of the fault zone is partly transferred to the east, ostensibly creating extension that is responsible for the closed basin Pyramid Lake is in. North of the Pyramid Lake fault zone may be a series of stepping normal faults that make up the western edge of the basin. Thus, the maximum length of the Pyramid Lake fault zone is 71 to 91 km (20 km vs. 40 km northern extension).

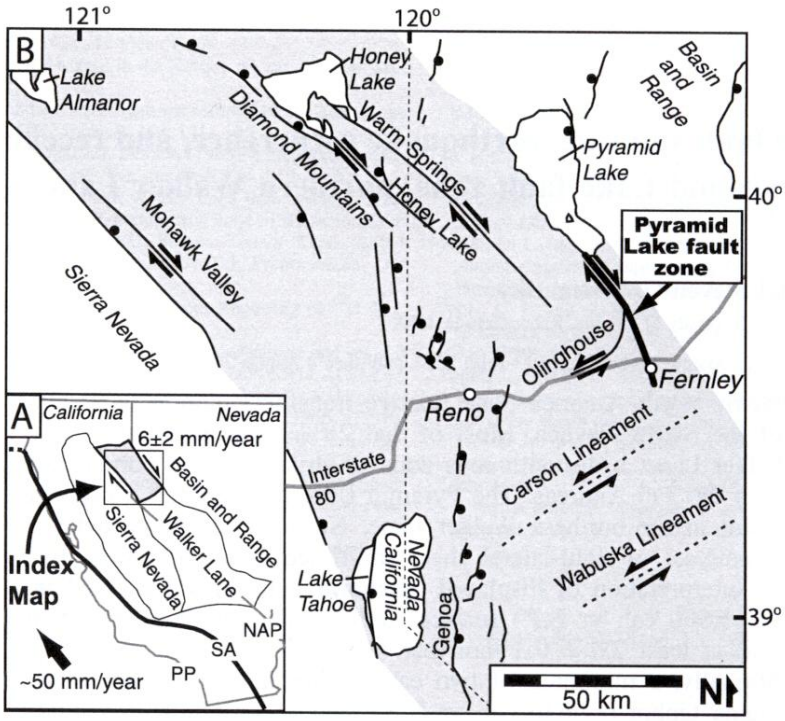

Figure 1. (a) Location of the northern Walker Lane (shaded) with respect to the San Andreas fault (SA) and the Sierra Nevada. Relative plate motion is from *DeMets and Dixon* [1999]. PP, Pacific plate; NA, North America plate. (b) Location of the Pyramid Lake fault zone with respect to known and suspected active faults of the northern Walker Lane. Circle is on the hanging wall of normal faults, and arrows show relative motion across strike-slip faults. Light shaded area denotes the approximate area of the northern Walker Lane.

(Figure from Briggs and Wesnousky, 2004)

Major Fault and Paleoseismic Investigations

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Anderson, L.W. and Hawkins, F.F., 1984, Recurrent Holocene strike-slip faulting, Pyramid Lake fault zone, western Nevada: Geology, v. 12, p. 681-684.

Anderson, L.W., LaForge, R., and Hawkins, F.F., 1984, Seismotectonic study for Lahontan Dam and vicinity, Newlands Project, Nevada: U.S. Bureau of Reclamation, Seismotectonic Section, Seismotectonic Report No. 84-1, 54 p. + appendices.

Briggs, R.W. and Wesnousky, S.G., 2004, Late Pleistocene fault slip rate, earthquake recurrence, and recency of slip along the Pyramid Lake fault zone, northern Walker Lane, United States: Journal of Geophysical Research, v. 109, B8, B08402, doi 10.1029/2003JB002717.

Geomorphic Expression

The Pyramid Lake fault zone has a wide range of expressions from classic strike-slip faulting geomorphology to large reaches of no surface expression whatsoever where buried by young sediments, erased by fluvial action, or destroyed by human cultivation and urbanization (Fernley). A detailed geomorphic map resulting from interpretation of aerial photographs and field work was presented in Briggs and Wesnousky (2004). Geomorphic expression is discontinuous and intermittent, yet this is arguably one of the most active earthquake faults in Nevada; this is a very important point indicating limitations for earthquake studies in Basin and Range Province that are based solely on surface expression of faulting.

Geomorphic features along the Pyramid Lake fault zone has fault scarps, back-facing scarps, closed depressions and pull-apart basins, right-laterally deflected stream channels and ridgelets, aligned drainages, linear ridges and depressions, right-laterally offset beach berms, vegetation and tonal lineaments.

Structural Description

The Pyramid Lake fault zone has been explored since 1968 (Bonham and Slemmons, 1968) and was mapped at a scale of 1:24,000 between Wadsworth and Pyramid Lake by Bell and others (2005a and 2005b). The zone is northwest striking, ranging from N14ºW in the south, to N40ºW along the northern part. The zone ranges in width from an apparently narrow, singular fault (approximately 100 m wide or less) up to 2 km wide where the zone intersects the Olinghouse fault.

The Pyramid Lake fault zone can be divided into four sections, the southern section, the Dodge Flat section, the Secret Canyon section, and the Pyramid Lake section. Each section has some difference in characteristics and/or is separated by a structural complication (discontinuity in the fault?).

The southern section extends nearly 15 km south of Fernley, and consists of scattered, discontinuous faults (Bell, 1984); Holocene activity is shown along the northern 5 km of this section (Bell, 1984). The southern end of the Pyramid Lake fault zone is undefined

and is structurally complex. Mapping by Faulds and Ramelli (2005) indicates the possibility that some of the strain from the Pyramid Lake fault zone steps to the southeast (Faulds, 2007, pers. comm.). The Virginia Range to the southwest has northeast-striking faults that may also intersect the Pyramid Lake fault zone, the southernmost of which are faults related to the Carson lineament. The best geomorphic expression along the southern section is confined to the part mapped with Holocene activity; Briggs and Wesnousky (2004) noted a "discontinuous series of roughly right-stepping grabens, uphill-facing scarps, and aligned mounds that extend to about seven km south of Fernley". The fault zone is difficult to trace through Fernley itself because of cultural activity, although it has been discovered in some consultant's trenches. Faulds and Ramelli (2005, 2006) have recently mapped some northwest-striking faults that are part of the zone within Fernley and to the east of Fernley.

The Dodge Flat section is about 16 km long. It is apparently fairly straight and narrow along the southern half of the section, although much of the fault zone is obscured by cultivation, recent fluvial activity, and eolian burial. Most of the fault along the Dodge Flat section is mapped as concealed or inferred (Bell and others, 2005a). The northern 7 km of the section (between Gardella Canyon and Dead Ox Wash) is a structurally complex zone, as much as 1.5 km wide, where the Olinghouse fault intersects the Pyramid Lake fault zone (Briggs and Wesnousky, 2004; Bell and others, 2005a). The Olinghouse fault appears to be a normal fault at its eastern reach (Briggs and Wesnousky, 2005) and intersects the Pyramid Lake fault zone at about a 35-40º angle. Several grabens are present near the intersection of these two faults that strike parallel to the main faults (Bell and others, 2005a).

One of the most studied sections of the Pyramid Lake fault zone is the Secret Canyon section, which has some of the best geomorphic expression along the zone, especially to the south and north of Secret Canyon where the main paleoseismic trenching sites are. The Secret Canyon section is about 15 km long, although the northern part is not structurally controlled, as much as it is buried by recent sediments and the water of Pyramid Lake. Briggs and Wesnousky (2004) describe this section as "manifested by springs, vegetation and tonal lineaments, tufa deposits, uphill-facing scarps, linear bedrock and alluvial ridges, and an unnamed elongate linear valley containing numerous closed depressions."

Little is known about the Pyramid Lake section because it is subaqueous. Briggs and Wesnousky (2004) commented that the Pyramid Lake fault zone continues "at most another 40 km beneath Pyramid Lake." Given the overall orientation of southern Pyramid Lake, especially the southwestern shore, it is very likely there is a northern continuation of the fault zone into the southern part of the lake. Not many features are obvious on available imagery of the bottom of the lake except one small, possible closed depression. Linear features on the floor of the lake near and south of Anahoe Island may be northeasterly striking faults that are intersecting the Pyramid Lake fault zone and distributing strain to the northeast. The Pyramid Lake fault zone may extend to just north of Anahoe Island; if this is true, the Pyramid Lake section would be about 20 km long.

Traditionally the Pyramid Lake fault zone has been considered a right-lateral strike-slip fault (Bonham and Slemmons, 1968; Bell and Slemmons, 1979; Anderson and Hawkins, 1984; Briggs and Wesnousky, 2004). Recently, Bell and House (2005) have challenged this strike-slip dominance, and proposed a more extensional nature to the zone. Bell and House stated:

> "In contrast, our detailed chronostratigraphic mapping of Lake Lahontan deposits suggests that most of the deformation along the PLFZ has apparently been extension-dominated during the late Quaternary."

Bell and House (2005) allow for a strike-slip component on one fault to explain the scissoring nature of the fault, but note a lack of detectible strike-slip offset in shorelines in the area of the graben that has been trenched by Anderson and Hawkins (1984) and Briggs and Wesnousky (2004). Bell and House (2005) further support their model with a fault strain ellipse argument, considering a "N60W-oriented shear strain (GPS) vector (Svarc et al., 2003), strain ellipse relations show that extension (not dextral shear) would dominate on the N20W-striking PLFZ."

Although Bell and House (2005) and Bell and others (2005a) documented a significant normal component along some faults in the zone, there are a number of indicators of strike-slip activity. These are right-lateral deflections of streams and berms, strike-slip geomorphology (e.g., linear ridges and back-facing scarps), and flower structures exposed in trenches. Nevertheless, the lack of more notable lateral offset of shoreline berms along the main fault in places is puzzling, and Bell and House are highlighting a normal component along the Pyramid Lake fault zone that is likely underappreciated.

Earthquake History

Two studies have investigated the earthquake history of the Pyramid Lake fault zone, Anderson and Hawkins (1984, also reported in Anderson and others, 1984) and Briggs and Wesnousky (2004). Both studies explored the same two sites with trenches, and came up with earthquake histories. The two interpretations of earthquake history have several similarities and a few differences. Here the two histories have been combined assuming that positive evidence of an event should be honored, even if it was not obvious in an adjacent trench. The largest difference between the two studies is the number of post-Mazama ash events.

The two sites that were trenched are nicknamed the "linear ridge site" (Anderson and Hawkins's (1984) Trench 1, and Briggs and Wesnousky's (2004) Secret Canyon North Trench) and the "graben site" (Anderson and Hawkins's (1984) Trench 2 and 2A, and Briggs and Wesnousky's (2004) Secret Canyon South Trench). This is for descriptive purposes. The two sites are a little over a kilometer apart and are located along the main fault strand.

Anderson and Hawkins (1984) and Anderson and others (1984) trenched the Pyramid Lake fault in a seismotectonic study of Lahontan Dam. They trenched the basal slope of an 800-m-long linear ridge (Trench 1) and a small pull-apart basin that forms a graben (Trenches 2 and 2A). Anderson and Hawkins (1984) found evidence of at least three, probably four, and possibly five events in Trench 1, and at least three and possibly four paleoearthquakes at Trench 2.

Linear ridge site

At the linear ridge site, the oversteepened base of the 10-m-high ridge and adjacent, ponded alluvium were trenched. The deposits that make up the ridge exposed in the trench are older alluvial deposits of Pre-Lahontan age (Anderson and Hawkins, 1984). The fault zone is at the base of the ridge and is the contact between the ridge deposits and adjacent deposits. The deposits west of the fault consist of lacustrine sand and beach gravels (Lake Lahontan deposits) overlain by fine-grained packages of silt, clay, and sand with some cobbly layers and large amounts of eolian input throughout (Anderson and Hawkins, 1984; Briggs and Wesnousky, 2004). The Mazama ash, colluvial packages shed from the ridge, and some soil horizons are also noted in these deposits.

Graben site

The graben site is made up mostly of debris flow and alluvial deposits. These are downdropped into the graben and there are additional deposits that are only within the graben (Briggs and Wesnousky, 2004). The Mazama ash is found throughout the trench exposure, within and outside of the graben. Colluvial deposits, shed off the faulted sides of the graben, were observed by both studies.

The eastern graben-bounding fault has apparent normal separation, whereas the western fault is more distributed (with a possible flower structure) and has an apparent reverse separation across it. Thus, the dominant strike-slip fault trace at the graben trenches appears to be the western trace.

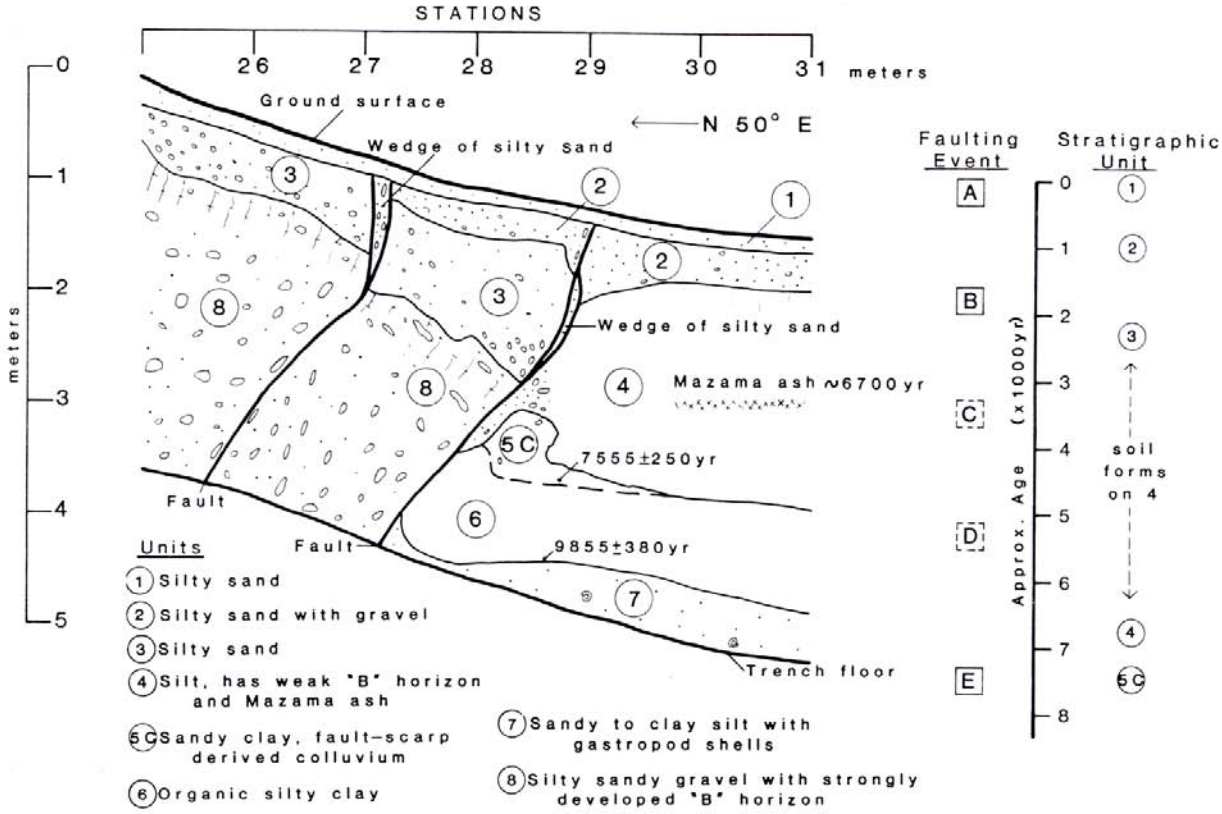


Figure 3. Log of central part of trench 1 with interpreted sequence of faulting events and approximate ages of units 1 through 5C.

Anderson and Hawkins (1984) linear ridge trench site log

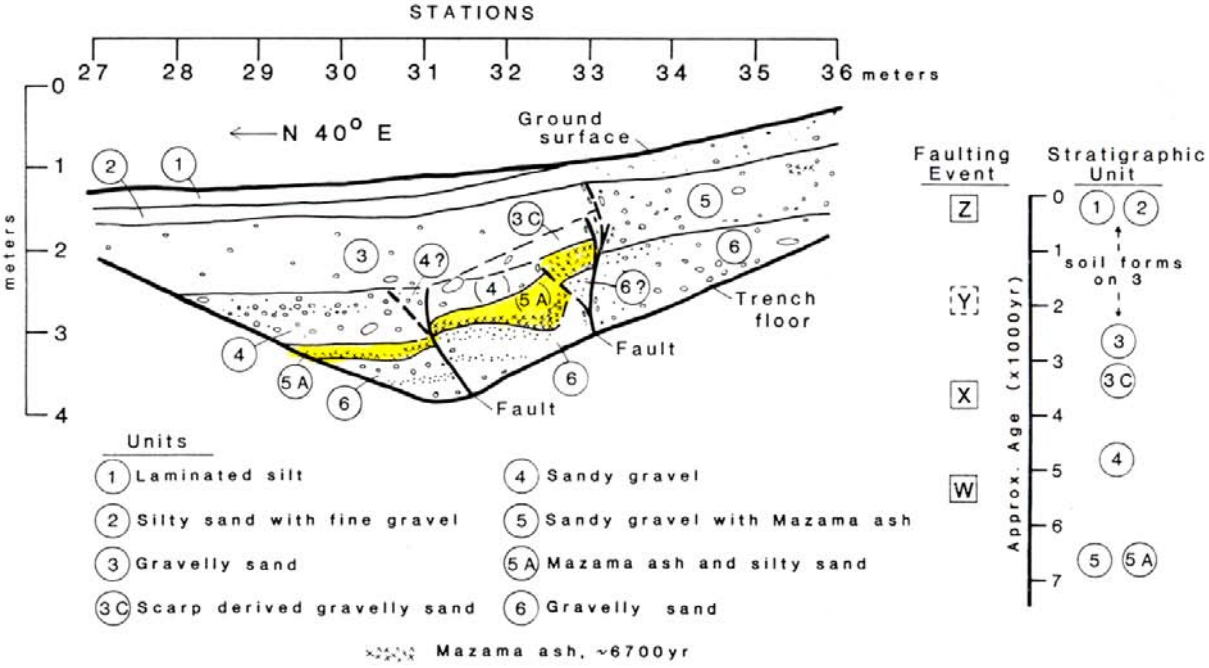
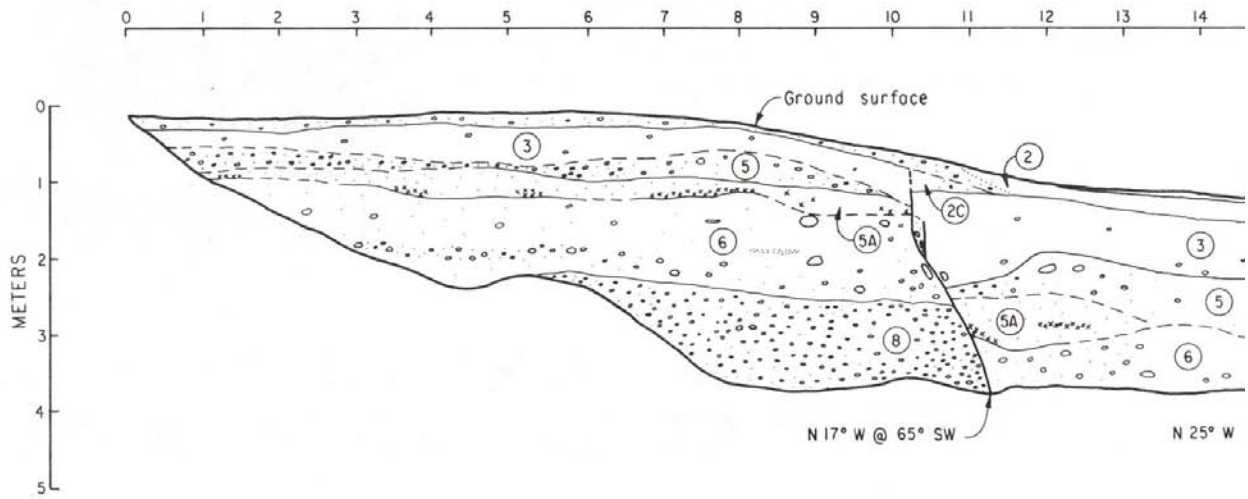


Figure 4. Log of part of trench 2A with interpreted sequence of faulting events and approximate ages of units 1 through 5A.

Anderson and Hawkins (1984) western side of graben trench log



DESCRIPTION OF TRENCH UNITS

(1) Dark grayish brown (2.5YR 4/2) silt, angular blocky to platy structure; ponded sediment; probably historic age.

(2) Brown (10YR 4/3) silty sand to sandy gravel, poorly stratified, deposit finer-grained within graben; slopewash colluvium and eolian sand; probably historic age.

(2C) Brown (10YR 4/2) silty sandy gravel, massive; slightly cemented; fault scarp derived colluvium.

(3) Brown (7.5YR 6/3-4/6) gravelly sand, massive, slightly cemented, has soil "B" horizon (see Appendix A) developed on it, "B" horizon pinches out at Sta. 12; debris flow and channel sand deposits.

(3A) Brown (7.5YR 6/3) sand, slightly cross-bedded; channel sand.

(3C) Brown (7.5YR 5/3) gravelly sand, massive, fault scarp derived colluvium.

(4) Brown (7.5YR 5/2) to dark brown (75.YR 3/2) sandy gravel, poorly bedded, clast supported pebbles, slight $CaCO_3$ coatings on some clasts; channel gravel.

(5) Light gray (10YR 7/1-7/2) to brown (7.5YR 5/4) sandy gravel to gravelly sand, poorly bedded to moderately well bedded, lenses of medium to coarse sand, Mazama ash present in pods and lenses; debris flow deposit.

(5A) Light gray (10YR 7/2) to white (10YR 8/1) gravelly silty sand, abundant Mazama ash present in pods, lenses, and beds, poorly bedded; debris flow deposit.

(6) Brown (7.5YR 5/3-4/3) sandy gravel, poorly bedded, occassional beds of medium to coarse sand; debris flow deposit.

(6A) Black (7.5YR 2/1) to light brown (7.5YR 6/3) pebbly sand, slightly bedded, subangular clasts; debris flow (?) deposit.

(7) Brown (7.5YR 5/4) gravelly sand (small boulders to coarse sand), massive, poorly sorted, clast supported; debris flow deposit.

(8) Brown (7.5YR 5/3) sandy gravel, poorly bedded. clast supported, slightly oxidized; debris flow deposit.

Faults; solid whe
(displacement

Contacts; solid
or approximate

Lenses, pods, or
ash (~6700 BP;

Anderson and others (1984) eastern side of graben trench

Briggs and Wesnousky (2004) engaged in a fairly comprehensive study of the Pyramid Lake fault zone with several sites; much of their paleoseismic evidence was gained from the same two sites as Anderson and Hawkins (1984), which greatly aids in meshing the two investigations. As might be expected, the Briggs and Wesnousky (2004) study is more modern with dendro-corrected radiocarbon dates, and they identified some tectonically induced colluvial deposits that appear to be good evidence of events. Briggs and Wesnousky (2004) interpret fewer events than Anderson and Hawkins (1984), but state, "Because we are interpreting the earthquake history from vertical offsets but the fault is strike-slip and the stratigraphy coarse, the observations only provide a minimum estimate of the number of events." Briggs and Wesnousky (2004) conclude that a, "minimum of two earthquakes have occurred since the deposition of the Mazama tephra (~7,630 cal. yr B.P.) and at least four earthquakes have occurred on the fault after dessication of Lake Lahontan (~15.5 ka), with the most recent earthquake occurring after 1,705 ±175 cal. yr B.P."

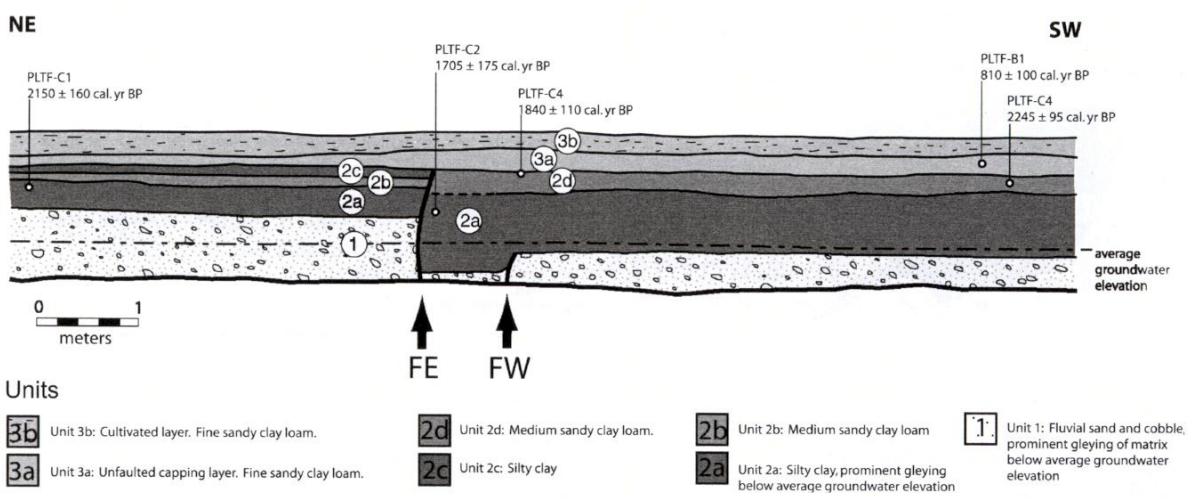


Figure 15. Trench log, Truckee River floodplain trench (see Figures 2, 4, and 14 for location).

Briggs and Wesnousky (2004) Truckee River floodplain trench site log

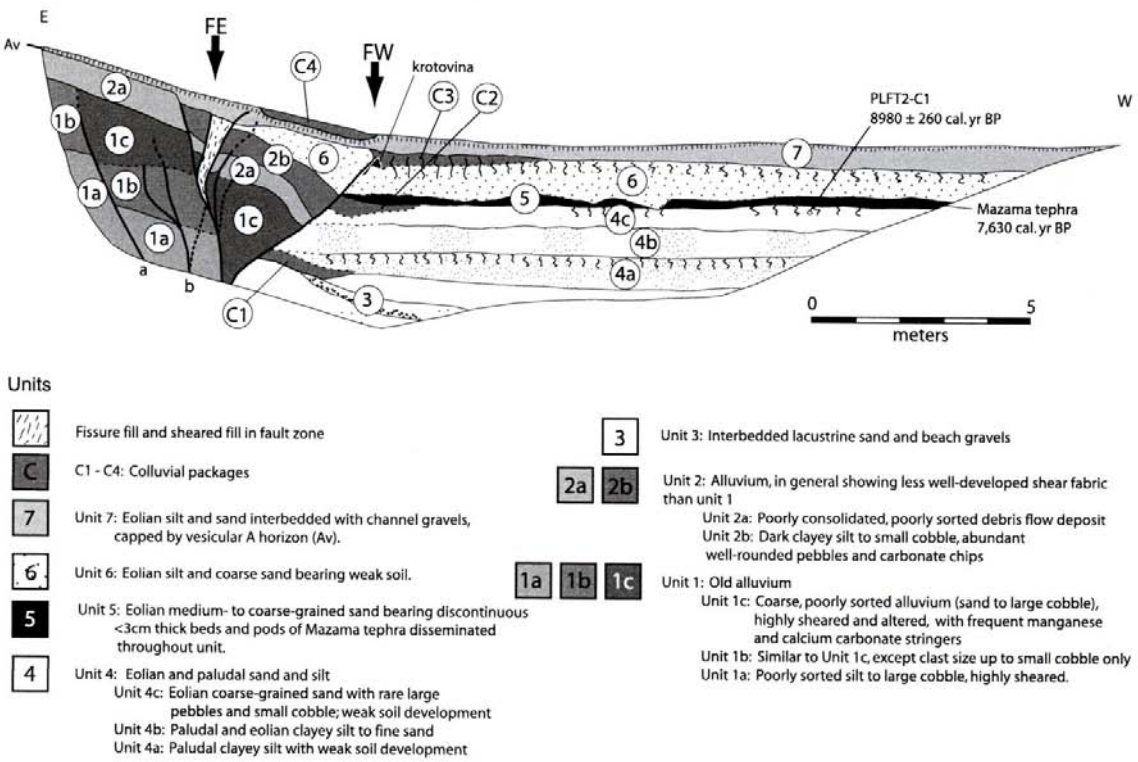


Figure 17. Trench log, Secret Canyon North trench (see Figures 2, 3, and 6 for location).

Briggs and Wesnousky (2004) linear ridge trench site log

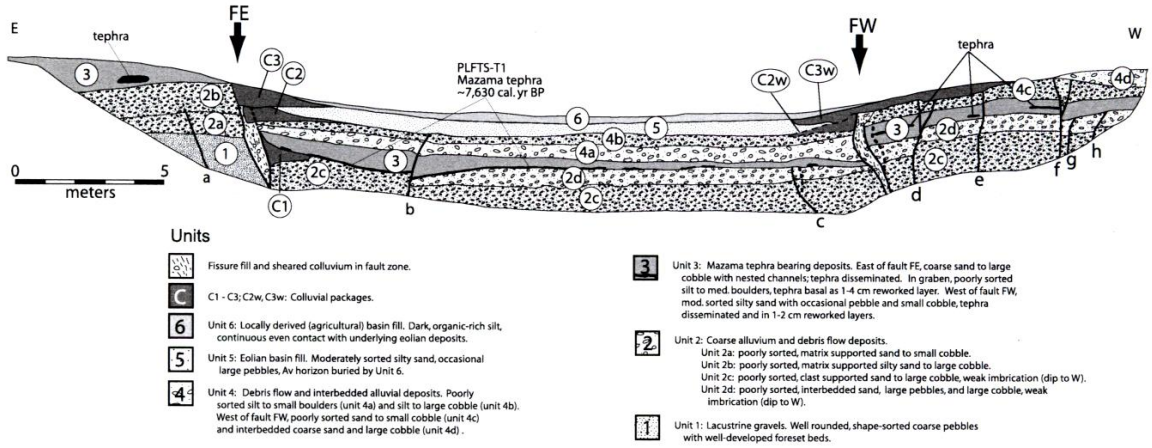


Figure 16. Trench log, Secret Canyon South trench (see Figures 2, 3, and 6 for location).

Briggs and Wesnousky (2004) graben trench site log

Two key units help correlate between Briggs and Wesnousky's (2004) Secret Canyon South Trench and Anderson and Hawkins (1984) and Anderson and others' (1984) Trench PL-2A (noted as logged by E. Baltzer and C. Krinsky; a partial log is shown by Anderson and Hawkins, 1984, whereas the entire log is reproduced in Anderson and others, 1984). The strongest correlation between the two trench logs is the Mazama ash, the only ash shown on the logs. The second correlation that is useful is colluvial wedge "C2w" of Briggs and Wesnousky and the colluvial wedge "3C" of Anderson and Hawkins (1984). This is the colluvial wedge developed after Paleoearthquake 2. The Mazama ash is the strongest correlation between Briggs and Wesnousky's Secret Canyon North Trench and Anderson and others' Trench PL-1 and the soil on Briggs and Wesnousky's unit 6 appears to correlate with the soil on top of unit 4S.

A combined paleoearthquake model that attempts to honor positive evidence of paleoearthquakes is summarized in Table 1. Anderson and Hawkins' (1984) paleoseismic model is presented along the side of their trench logs. Briggs and Wesnousky's (2004) paleoseismic model is presented in the figure following Table 1.

Table 1 Paleoearthquake Model for the Pyramid Lake Fault Zone

Event	**Corrected Age Control**		
PE1	60 – 710 ybp	to	1,880 ybp
PE2	?	to	<< Mazama Ash (7,480 – 7,780 ybp)
PE3	?	to	< Mazama Ash (7,480 – 7,780 ybp)
PE4	7,570 ybp	to	9,240 ybp
PE5	10,280 ybp	to	15,950 ybp (highstand)

Radiocarbon dates have been calendar corrected using Stuiver and Reimer (1993) and Reimer and others (2004). Calendar corrected dates are two-sigma ranges rounded to the nearest 10th place when reported.

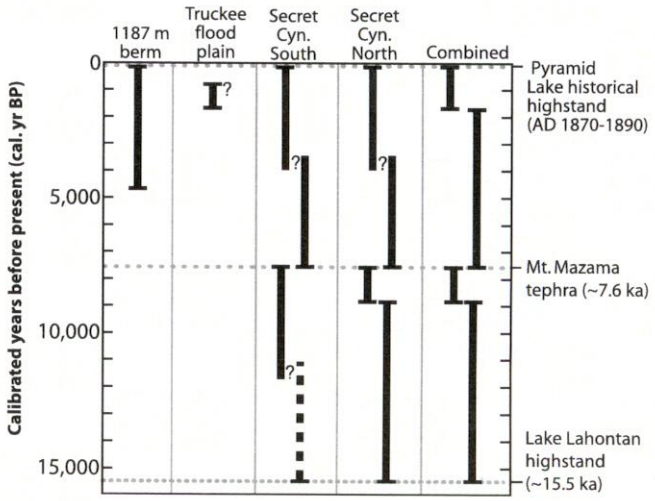


Figure 18. Summary of paleoearthquake timing as interpreted from trench exposures and unfaulted surfaces. Solid bars represent time interval during which each earthquake may have occurred; dashed bar is an ambiguous event.

(From Briggs and Wesnousky, 2004)

Historical or very young paleoearthquake

Anderson and Hawkins (1984) inferred a very young event at their Trench 2 & 2A site, commenting:

> "Event Z probably occurred within the past few hundred years. Unit 2, the only unfaulted horizon, appeared to be very young (possibly historic) on the basis of similarities to modern wash deposits."

They further stated that there are two local, possible historical events, the 1852 and the 1860 earthquakes may have caused this surface expression. Research with California newspapers by Craig dePolo, Nevada Bureau of Mines and Geology, and Tousson Toppozada, California Geological Survey, rule out a large earthquake in western Nevada in 1852, and push this event, for which there are Native American accounts, back to the 1840s (unpublished research), and likely in the eastern Carson Sink region. The 1860 earthquake is thought to have occurred in the southern Pyramid Lake region (Toppozada and others, 1981) and thus could be a candidate for the young faulting event proposed by Anderson and Hawkins (1984).

This evidence presented by Anderson and Hawkins (1984) is minimum limiting evidence. Thus, an event of one to two thousand years old could be consistent with their data.

Briggs and Wesnousky's (2004) youngest event at the Truckee River floodplain trench site offsets deposits dated 1,705 ±175 cal. ybp (PLTF-C2), is likely older than deposits with a bone dated at 810 ±100 cal. ybp (PLTF-B1), and is definitely older than sediments associated with the historical highstand (1870-1890 AD). Briggs and Wesnousky (2004) made the following comment about a possible historical earthquake along the Pyramid

Lake fault:

> "The fault scarps we observe are relatively subdued, especially in the central … and southern … section[s] of the fault, and there are relatively few unequivocal laterally displaced features over much of the length of the fault. While the possibility that a historical surface rupturing earthquake occurred on the Pyramid Lake fault is allowed by geologic observations, the 810 ±100 cal yr B.P. bone preserved in the unfaulted capping layer of the Truckee trench … suggests to us otherwise."

If there was a historical earthquake along the Pyramid Lake fault zone, faulting would have had to have missed or gone under the Truckee River floodplain trench site, and surface expression was subdued.

Paleoearthquake 1

Paleoearthquake 1 (PE1) is best defined by Briggs and Wesnousky (2004) in their Truckee River floodplain trench site. The youngest event at that site offsets alluvial deposits (units 2a-d) that contain detrital charcoal, the youngest of which is dated 1705 ±175 cal. ybp. The event is likely older than a bone from overlying, unfaulted deposits (unit 3a), radiocarbon dated at 810 ±100 cal. ybp, although it cannot be ruled out that the bone is significantly older than the deposit (Briggs and Wesnousky, 2004). Briggs and Wesnousky (2004) note that PE1 is definitely older than unfaulted sediments associated with the historical highstand (1870-1890 AD). At Briggs and Wesnousky's (2004) Secret Canyon South Trench, they found colluvial deposits from PE1 on both sides of the graben (units C3 and C3w), with the eastern side having a classic colluvial wedge shape. This colluvial wedge is an active surficial deposit with only its toe buried by very young graben fill. Colluvial wedge C3w also has its toe buried by the youngest graben-fill deposit, and overlies two truncated fault traces (faults d and e). In Briggs and Wesnousky's (2004) Secret Canyon North Trench where they stated:

> "The most recent event may be represented by displacement of unit 7 along a poorly expressed strand of fault FE and capture of coarse slope colluvium (unit C4) between strands FE and FW."

This colluvium was captured on top of the flower structure wedge exposed in the trench.

This event approximately correlates with Anderson and Hawkins' (1984) event A (their Trench PL-1) and event Z (their Trench PL-2A). In Trench PL-1, the most recent event offset unit 2 and is buried by a thin very young deposit (unit 1). In Trench PL-2, Anderson and others (1984) identified a small colluvial wedge (unit 2C) on the east side of the graben, which is buried by a thin, very young deposit (unit 1).

The best evidence indicates that Paleoearthquake 1 occurred between 810 ±100 ybp and 1,705 ±175 ybp (Briggs and Wesnousky, 2004). Paleoearthquake 1 is definitely older

than the historical highstand (1870-1890 AD or 60-80 ybp where p=1950; Briggs and Wesnousky, 2004). Therefore PE1 occurred between 60 – 710 ybp and 1,880 ybp.

Paleoearthquake 2

Evidence for Paleoearthquake 2 is fairly distinct at the graben site and is reasonably clear at the linear ridge site. At the graben site (Secret Canyon South Trench) Briggs and Wesnousky (2004) mapped paired colluvial wedges on the east and west sides of the graben (units C2 and C2w), buttressed against faults. In Anderson and Hawkins's (1984) Trench 2A, a correlative colluvial wedge was found on the west side (unit 3C). In Anderson and others' (1984) Trench 2, no colluvial wedges were identified, but faulting or possible deformation of the base of unit 3 is indicated, which could have been caused by PE2. Anderson and Hawkins (1984) identified a soil on top of unit 3 and stated:

> "Unit 3 has a moderately developed soil (similar to the soil development on unit 4 in Trench 1), which probably required several thousand years to form."

If all young events are represented in Trench 2A, then this soil potentially formed between PE2 and PE1; the soil is a natric horizon (Anderson and Hawkins, 1984) which can form relatively quickly.

At the linear ridge site, Briggs and Wesnousky (2004) mapped a colluvial wedge deposit (unit C3) at the base of the flower structure marking the main fault; this wedge overlies a soil formed in the top of unit 6, which overlies the Mazama ash. Additional shearing on the eastern side of the flower structure (fault FE) also seems to have occurred during PE2, creating a slight depression that unit 7 is deposited (a thickening of unit 7 occurs over this part of the flower structure). Evidence for Paleoearthquake 2 in Anderson and Hawkins's (1984) Trench PL-1 is a "V-shaped depression near station 29" created just before the deposition of unit 2, that created all or part of the faulted juxtaposition of unit 3 with unit 4.

Paleoearthquake 3

Anderson and Hawkins (1984) found evidence for an event that is older than PE2 but younger than the Mazama ash in Trench PL-2A. This is deformation of unit 5A (which contains the Mazama ash) that is not in the overlying unit 4, which in turn lies under the colluvial wedge from PE2 (unit 3C). The key observation is the non-deformation of unit 4. In Trench PL-1, this event may have caused part of the juxtaposition of unit 3 against unit 4 with apparently not much vertical offset to induce the formation of a colluvial deposit. This event may also have formed a fissure at the fault in unit 5c, which is infilled by unit 4.

Briggs and Wesnousky (2004) did not have an event during this time interval, their next oldest event before PE2 being pre-Mazama ash. There is a graben-bounded unit (4a) on their log that seems to be an additional unit relative to outside of the graben, and has a

long wedge shape, tapered on the east side, and at its maximum thickness it is buttressed against the western fault trace (fault FW). This deposit could be related to a PE3 offset on fault FW (unit 4a would correlate to Anderson and Hawkins's (1984) unit 4). At the Secret Canyon North trench, PE3 offsets could have occurred on fault FE, with any record of the event eroded away.

Paleoearthquake 3 is assigned a post-Mazama ash age to honor the positive evidence presented for the event by Anderson and Hawkins (1984), and because, although no evidence was found for this event in Briggs and Wesnousky's (2004) study, it isn't ruled out by their study and is permissive in their logs. PE3 is older than PE2 and younger than Mazama ash (7,477 – 7,777 cal. ybp; Zdanowicz and others, 1999), but there are no other constraints at this time.

Paleoearthquake 4

Both Anderson and Hawkins (1984) and Briggs and Wesnousky (2004) identified an event occurring shortly before the Mt. Mazama eruption of the local ash, herein recognized as Paleoearthquake 4. At Trench PL-1, PE4 (Anderson and Hawkins's (1984) event E) is the oldest event they identified. It has been bracketed by radiocarbon dates and is older than the Mazama ash. PE4 created a colluvial wedge, part of which was exposed (unit 5C). Unit 5C has a bulk radiocarbon date from near the base of the colluvium of 7,555 ±250 ^{14}C ybp (sample # GX-50054), which provides a minimum age for PE4. This "block of fault-scarp-derived colluvium" immediately underlies a silt deposit (unit 4) that contains the Mazama ash. The earthquake faulted unit 6 which has a radiocarbon date of 9,855 ±389 ^{14}C ybp (sample # GX-10055), which provides a maximum age for this event (Anderson and Hawkins, 1984).

Briggs and Wesnousky (2004) also found a colluvial wedge from PE4 (unit C2) at the Secret Canyon North Trench site, immediately underlying the deposit that contains Mazama ash. Unit C2 lies immediately on top of unit 4C from which detrital charcoal was radiocarbon dated and calendar corrected to be 8,980 ±260 cal. ybp (sample # PLFT2-C1), which predates PE4. At the Secret Canyon South Trench site a colluvial wedge was formed following this event (unit C1) that immediately underlies the deposit containing Mazama ash; this is on the eastern side of the graben. There is also a fault strand (fault C) within the graben on the west side that is truncated by the Mazama ash bearing deposit.

Paleoearthquake 4 is one of the best dated events along the Pyramid lake fault zone, with two dates preceding the event and two dates following it. Before the event are Anderson and Hawkins (1984) date calendar corrected to 10,275 – 12,626 cal. ybp and the more constraining maximum date from Briggs and Wesnousky (2004) of 8,720 – 9,240 cal. ybp.

Following PE4 is Mazama ash (7,477 – 7,777 cal. ybp; Zdanowicz and others, 1999), and the more constraining minimum date from Anderson and Hawkins (1984) 7,872 – 9,004 cal. ybp. This date is from "organic fine sediment of probable pedogenic origin" and is

potentially subject to a mean residence time (MRT) correction (this is an apparent age of the soil, or aging of the soil due to inclusion of older detrital organic matter). No local correction has been proposed, so large range of potential values from 50 to 300 years is used; the 50 years was proposed for the Carson Range fault system by Ramelli and others (1994) and the 300 years is one of the oldest proposed in the Basin and Range Province for the Wasatch front (e.g., Forman and Miller, 1989). If a maximum of 300 years is subtracted from the minimum value of 7,872, it becomes 7,572 (in other words, the deposit may be younger than the date).

Using these constraints, Paleoearthquake 4 can be bracketed between 7,570 to 9,240 ybp.

Paleoearthquake 5

Evidence for Paleoearthquake 5 at the Secret Canyon North Site includes a colluvial wedge (unit C1) formed on top of Lake Lahontan lacustrine sands and gravels (Briggs and Wesnousky, 2004). If Briggs and Wesnousky's (2004) "unit C1" is age correlative with Anderson and Hawkins' (1984) "unit 6" tehn PE5 would be older than a radiocarbon date of 9,855 ±380 ^{14}C ybp found at the bottom of unit 6.

At Briggs and Wesnousky's (2004) Secret Canyon South Trench site, fault a is "ambiguously truncated by unit 2b," a deposit that is older than deposits with Mazama ash.

Paleoearthquake 5 is thought to have occurred shortly after the highstand of Lake Lahontan, reported as ~15.5 ka by Briggs and Wesnousky (2004), and likely just before before Anderson and Hawkins (1984) calendar corrected date, 10,275 – 12,626 cal. ybp. Paleoearthquake 5 occurred significantly earlier than Briggs and Wesnousky's (2004) date of 8,720 – 9,240 cal. ybp, which was taken about 0.5 m above unit C1; there is also a soil between this date and unit C1. Calendar correcting dates from Adams and Wesnousky (1998) gives an age range of the highstand to be 15,117 to 15,946 cal. ybp. Thus, Paleoearthquake 5 occurred between 10,280 and 15,950 ybp.

Additional young event? (PE1.5?)

Anderson and Hawkins (1984) noted that there is a well-developed natric horizon (argillic horizon that is sodium-rich) in both the trench sites that is younger than the Mazama ash. At the graben site there is one paleoevent identified above the soil, whereas at the linear ridge site there are two events after the formation of this soil. If these two soils are contemporary, they provide a tie between the two trench sites and there is an additional event in the Pyramid Lake fault zone chronosequence (Anderson and Hawkins, 1984, event Y?). This would be Paleoearthquake 1.5. If this is true, PE1.5 is not evident at the graben site, with evidence perhaps eroded away. At the Secret Canyon South Trench, Briggs and Wesnousky's (2004) unit 5 appears to correlate with Anderson and Hawkins's (1984) unit 3 (at least the upper part). There is no evidence for an event between this unit and the colluvial deposits from PE1 that would support an additional event before the soil in unit 3. Anderson and Hawkins (1984) cited a complex

juxtaposition of units at the graben site as possible evidence for this additional event, but strike-slip motion may have caused this juxtaposition as well.

The alternative hypothesis is that these soils formed over different time periods and are not time correlative, and the general post-Mazama ash paleoseismic record at both trench sites is the same three events. This is the hypothesis adopted here.

Fault Slip Rates

Briggs and Wesnousky (2004) calculated fault slip rates at three locations along the Pyramid Lake fault zone, called sites A, B, and C.

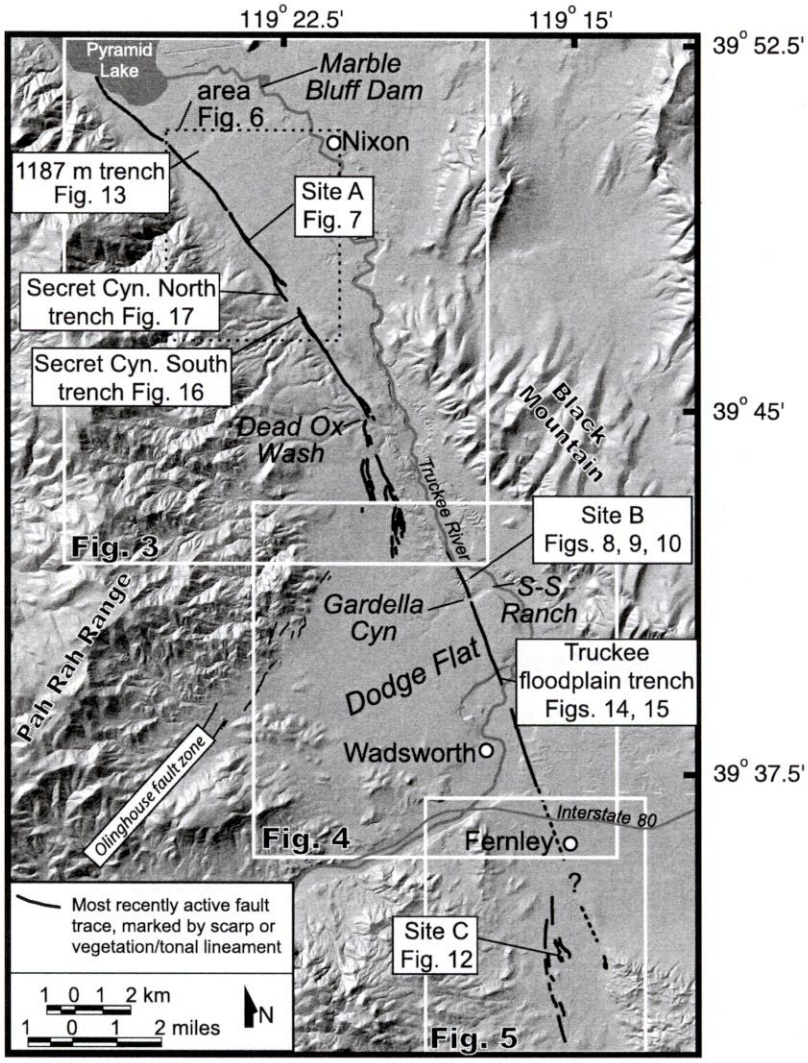


Figure 2. Location of the Pyramid Lake fault zone with respect to Pyramid Lake, Fernley, and Interstate 80. Slip rate sites A–C, trench locations, and outlines of Figures 3–6 are also shown.

From Briggs and Wesnousky (2004)

The northernmost site (site A) is a post-Lake Lahontan highstand channel bank offset right-laterally by 12 to 15 m (Briggs and Wesnousky, 2004). The time constraint of the highstand of Lake Lahontan (~15.5 ka) is used by Briggs and Wesnousky (2004) in their slip rate estimate. Assuming the offset was created by multiple earthquakes, Briggs and Wesnousky (2004) calculate a minimum slip rate of ~0.7 – 1.0 m/ky.

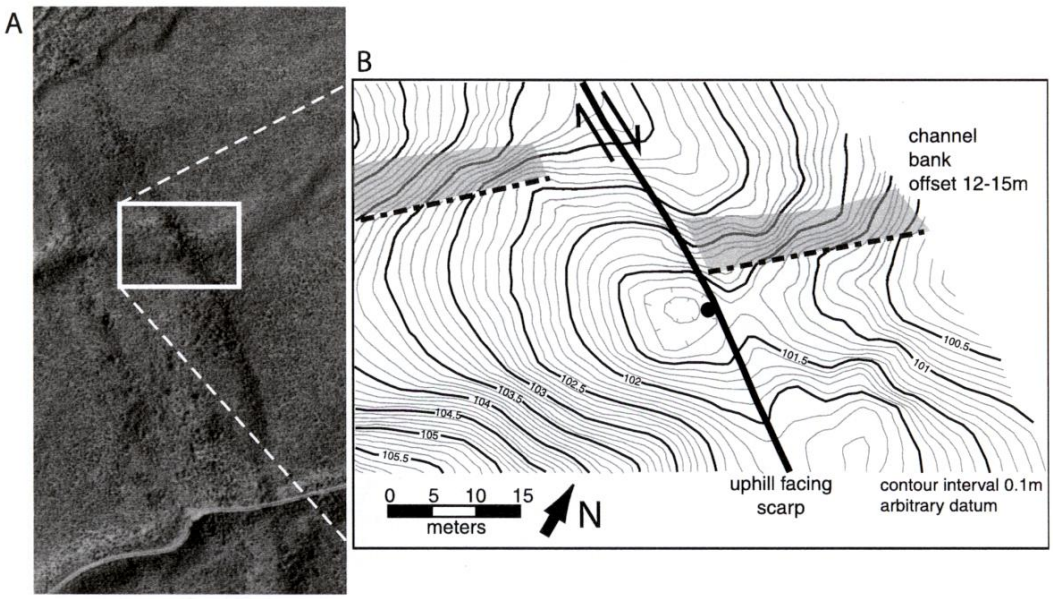


Figure 7. Site A. (a) Vertical low Sun angle air photo and (b) contour map showing offset of channel bank. Total offset is 12–15 m (see Figure 6 for location).

(Figure 7 is from Briggs and Wesnousky, 2004)

Briggs and Wesnousky's (2004) site B is just north of Dodge Flat. A series of canyons formed by headward erosion into the walls of the Truckee River Canyon are truncated and right-laterally offset by the Pyramid Lake fault zone (Briggs and Wesnousky, 2004). Briggs and Wesnousky (2004) state, " Topographic mapping, vertical air photo reconstruction, and field measurements of channel thalweg, channel margin, and ridge crest offsets yield total right-lateral displacement of 35-43 m." A local trench was used to confirm the collocation of the fault and these ridge offsets. Briggs and Wesnousky (2004) noted that, "numerous geomorphic and stratigraphic relations suggest thata the Truckee River canyon, and hence the offset side canyons at site B, formed after the desiccation of Lake Lahontan at ~15.5 ka." Using the 35-43 m right-lateral offset and ~15.5 ka gives a minimum bound on the slip rate of 2.6 ±0.3 m/ky (Briggs and Wesnousky, 2004, consider this a minimum because the offset occurred after ~15.5 ka – but if an event occurred shortly after the lake receded as possibly indicated by colluvial wedge "C1" of the Secret Canyon North Trench site lying directly on lacustrine sediments, then this rate may not really be much of a minimum and may be more in the "expected" range).

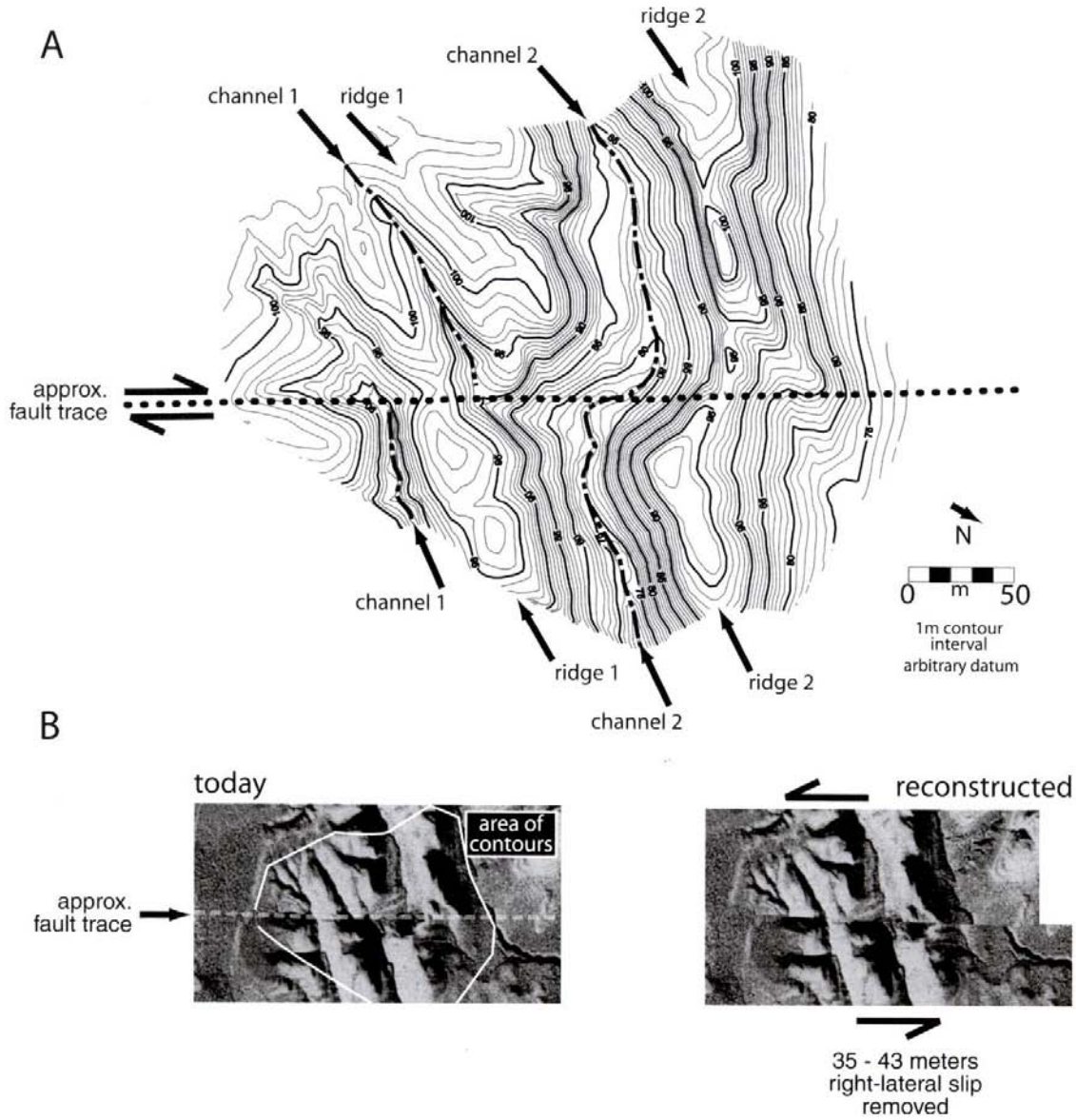


Figure 9. Site B. (a) Topographic map of offset ridges and channels of side canyons at site B. (b) Vertical air photo of offset features showing 35–43 m right-lateral slip restored (see Figures 2 and 4 for location).

(Figure 9 is from Briggs and Wesnousky, 2004)

A third site study by Briggs and Wesnousky (2004) is south of the town of Fernley (site C) where a "shallow channel formed in post-Lake Lahontan alluvium that is offset 13-15 m in a right-lateral sense and is now beheaded against the fault scarp." Briggs and Wesnousky (2004) noted that the channel offset does not include near-fault deformation and the offset is a minimum. Again using the post-Lahontan time (~15.5 ka) and an assumption of multiple earthquakes, Briggs and Wesnousky (2004) calculated a minimum fault slip rate of 0.8 – 1.0 m/ky for site C.

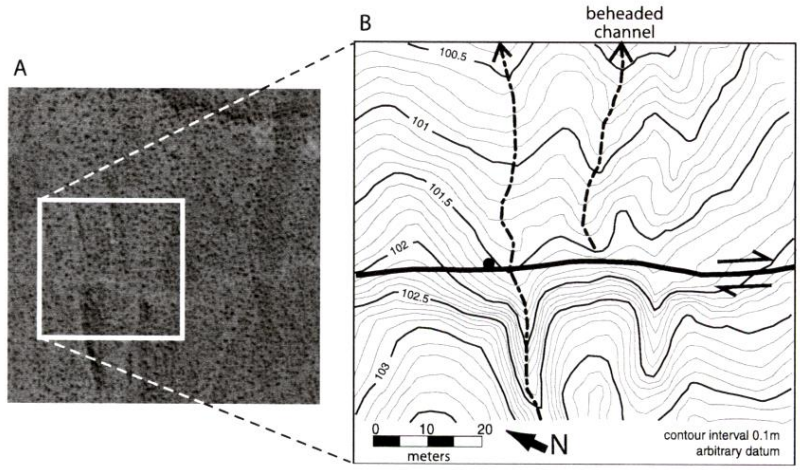


Figure 12. Site C. (a) Vertical low Sun angle air photo and (b) contour map showing beheaded channel. Total offset is 13–15 m (see Figures 2 and 5 for location).

(Figure 12 is from Briggs and Wesnousky, 2004)

Bell and House (2005) calculated a vertical slip rate for the portion of Pyramid Lake fault zone that they studied. They measured a 10 to 26 m vertical offset of deposits that are 12 to 30 ka old, giving a vertical slip rate of as much as 0.87 m/ky.

In two cases Briggs and Wesnousky (2004) calculated minimum slip rates rates for the last 15.5 ky of ~0.7 to 1 m/ky for the Pyramid Lake fault zone. The largest rate they calculated was 2.6 ±0.3 m/ky.

Earthquake Recurrence Intervals

Two average earthquake recurrence intervals for the Pyramid Lake fault zone have been reported. Anderson and Hawkins (1984) stated, "The estimated average recurrence of surface faulting events (Ms≥ 6.5) is about 1,800 yr assuming four post-Mazama-ash events and about 2,400 yr for three events." Using a more modern estimate of Mazama ash age (~7.6 ka), Anderson and Hawkins' (1984) recurrence interval becomes 1,900 - 2,430 years (Briggs and Wesnousky, 2004). Briggs and Wesnousky (2004) stated, "A composite of the paleoearthquake records from all trenches … suggests that three earthquakes occurred after 8,980 ± 260 cal. yr B.P. with an average recurrence interval of ~ 2,910 - 3,080 years."

Using the combined earthquake chronology presented here, four earthquake interseismic intervals are present. Paleoearthquake 5 is assumed to have occurred shortly after the dessication of Lake Lahontan, so the highstand age of ~15.5 ka can be used as a maximum time period. Calendar correcting dates from Adams and Wesnousky (1998) gives an age range of the highstand to be 15,120 to 15,950 cal. ybp. There are four interseismic intervals to PE1. Paleoearthquake 1 occurred between 60 and 1,710 ybp.

The time since PE1 needs to be subtracted from the time since PE5 to isolate the time of the four interseismic intervals. Thus, the time frame over which the four interseismic intervals occurred using the given data is 13,800 to 15,890 years. These are divided by four to give an average interseismic interval of 3,450 to 3,973 years over the last ~15.5 ky.

Using the combined earthquake chronology, there are three post-Mazama ash (7,480 – 7,780 ybp) events. This gives two interseismic intervals over the time period of 5,770 to 7,720 years (subtracting the time since PE1), or an average interseismic interval of 2,885 to 3,860 years.

If the number of post-Mazama tephra earthquakes is actually four as proposed by Anderson and Hawkins (1984) rather than three (see earlier discussion), the interseismic interval estimates would decrease the range to 1,900 to 3,100 years.

Estimations of the average earthquake recurrence intervals along the Pyramid Lake fault zone range from 2,900 to 3,800 years.

Earthquake Segmentation

No segmentation has been proposed for the Pyramid Lake fault zone. The largest discontinuity and structurally most complex part of the fault zone is where the Olinghouse fault intersects the zone. The strike of the Pyramid Lake fault zone changes slightly across this discontinuity

Single-Event Displacements

Briggs and Wesnousky (2004) back-calculated single-event displacements based on their estimates of slip rates and recurrence intervals (both calculated independently). Their calculated average earthquake recurrence interval of ~2,910 - 3,080 years and slip rate estimate of 2.6 ±0.3 m/ky implies a single-event displacement of 6.7 to 8.9 m (Briggs and Wesnousky, 2004). Using Anderson and Hawkins' (1984) recurrence interval with an adjusted Mazama ash time gives single-event displacement of 5.9 ± 1.4 m. Briggs and Wesnousky (2004) noted that there is a possibly that the Pyramid Lake fault zone ruptures with infrequent but large earthquakes, and thus offsets at slip rate sites A and C could be single-event offsets (12-15 m and 13-15 m). Given that there are at least four to five events documented along the Pyramid Lake fault zone since the Lake Lahontan highstand, it seems unlikely that these large offsets are single-event offsets, however.

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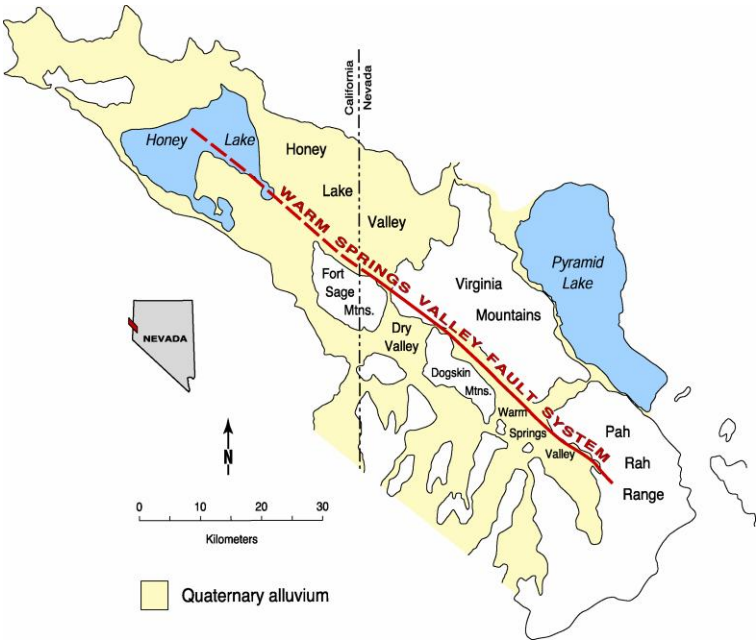
Nevada Quaternary Fault Working Group FAULT FORM **<u>Warm Springs Valley fault system</u>**

Fault Name

Warm Springs Valley fault system
USGS Fault and Fold Database fault # 1605



Introduction

The Warm Springs Valley fault system is a major, right-lateral fault in western Nevada, ~20 km north of Reno, and is one of the large, subparallel strike-slip faults in the northern Walker Lane. The system crosses valleys that are planned to be the main expansion corridor for Reno, and home building has steadily encroached on the southern quarter of the system. Where the fault forms a trough between ranges, developments are being planned in a swath right along the faults.

Location and Length

The Warm Springs Valley fault system crosses several different valleys and mountain flanks in northwestern Nevada and northeastern California. The southern end of the system is in the western flank of the Pah Rah Range. The fault system is discontinuously expressed across the northeastern part of Warm Springs Valley, its namesake, and continues northward through a valley that is elongate along the fault, Winnemucca Valley (between the Dogskin Mountains and the Virginia Mountains). North of this, faults are formed in the western flank of the Virginia Range and the eastern piedmont of the Fort Sage Mountains, and project northwestward out into Honey Lake Valley.

The Warm Springs Valley fault system is a nearly continuous series of faults that extend for about 54 km in Nevada and may be as much as 96 km long including a likely northern extension into Honey Lake Valley in California. There are breaks in the continuity of the geomorphic features where young basin sediments cover them and where crossed by young fluvial deposits and fans.

Major Fault and Paleoseismic Investigations (chronological order)

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Geomorphic Expression

The Warm Springs Valley fault system crosses several different topographic terrains, such as being in the flanks of mountains, having central basin positions, and crossing alluvial piedmonts. In each of these settings the fault system has a different geomorphic expression. Many of the features along the Warm Springs Valley fault system are characteristic of strike-slip faulting, such as linear ridges and troughs, deflected drainages, shutter ridges, and push-up mounds. Nevertheless, the system has a wide variety of geomorphic features, including normal dip-slip fault features where it forms a large pull-apart basin. Thirty-nine different types of geomorphic features were identified along the Warm Springs Valley fault system by dePolo and Ramelli (2004), who made a geomorphic map of it at a scale of 1:24,000. Many of the geomorphic features have a northwest orientation, parallel to the system.

Using the three settings of the Warm Springs Valley fault system, alluvial basins, piedmonts, and bedrock areas, the system was divided into five geomorphic sections by dePolo and Ramelli (2004). The are, south to north: the Pah Rah Range section, the Warm Springs Valley section, the Winnemucca Valley section, the Virginia Mountains section, and the Honey Lake Valley section.

The Warm Springs Valley section and Honey Lake Valley sections are alluvial basins where faults have discontinuous surface expression. Holocene sedimentation 0.5 to 2 m thick has occurred and along with earlier sedimentation has tended to bury earthquake created features. When features are formed in these sediments they can erode very easily. Only geomorphic features related to latest Pleistocene and Holocene events are visible, and there are large gaps in landforms where Holocene burial has occurred. There are numerous drainage, tonal, and vegetation lineaments along the fault within these landform gaps, but they are equivocal as to whether they are related to faulting or not.

In the Winnemucca Valley section, and parts of other sections, the Warm Springs Valley fault system is in Quaternary piedmonts. Along these reaches, middle and late Pleistocene features, such as linear ridges and compound fault scarps, are nearly continuous. The piedmonts and fans tend to be disrupted by the fault zone, and sediments pond behind it or are deflected around it.

In the Virginia Mountains section, just south of Honey Lake Valley, the fault system is in bedrock terrain with relatively little Quaternary burial, creates a large pull apart basin (5 to 6 km long), and crosses the northeastern flank and piedmont of the Fort Sage Mountains. The geomorphic evidence of long-term activity is reasonably pronounced, with the large pull-apart basin, large-scale stream deflections, and linear and shutter ridges. Very youthful geomorphic features are subtle however, perhaps due to the fault zone itself, which is sheared fault gouge where exposed and is easily eroded. The Pah Rah Range section also is in bedrock terrain (at least the eastern part) where the fault forms a corner pull-apart basin near system's southern end within the range and partly coincides with mapped bedrock faults.

Structural Description

The Warm Springs Valley fault system is a major right-lateral strike-slip fault system that is as much as 96 km long (dePolo and Ramelli, 2004), and has total right lateral offsets of 10 to 15 km based on offset Tertiary river channels (Faulds and others, 2005). Recent right-lateral strike-slip movement has been proven in Warm Springs Valley by box trenching of a paleo-stream channel which is laterally offset at the fault plane (dePolo, 2006). The system commonly includes two or more fault traces in parallel and anastomosing patterns. The fault zone width is commonly about 1 km, but it is as much as 2 km around complexities, such as the large pull-apart basin. The system has two overall orientations, ~N40ºW along the southern portion, and ~N55ºW along the northern portion, with the change occurring near the boundary between the Winnemucca Valley and the Virginia Mountains sections, about halfway up the system.

The southern part of the system seems to partly be distributed into southern Warms Springs Valley, likely forming a pull-apart basin within the valley based on gravity data (Gimlett, 1967; Widmer, 2001) and ultimately intersects the northeast-striking Spanish Springs Peak fault zone. The northern part of the system is buried in Honey Lake Valley; the shape of Honey Lake indicates the fault system likely makes it at least that far, and there is more basin to the northwest of that.

The Warm Springs Valley fault system is a quintessential transtensional fault. Although all kinds of faults have been found in trenches, including reverse dip-slip faults, there is a tendency for the fault system to have right steps in it, with the associated extension; there are some left steps, but the tendency is to the right. The system also crosses large basins without forming any significant positive relief. Where the system crosses bedrock areas, there are pull-apart basins also supporting an extensional component. The overall extension across the fault has been hard to quantify because it is distributed, secondary,

and structurally expressed in different ways.

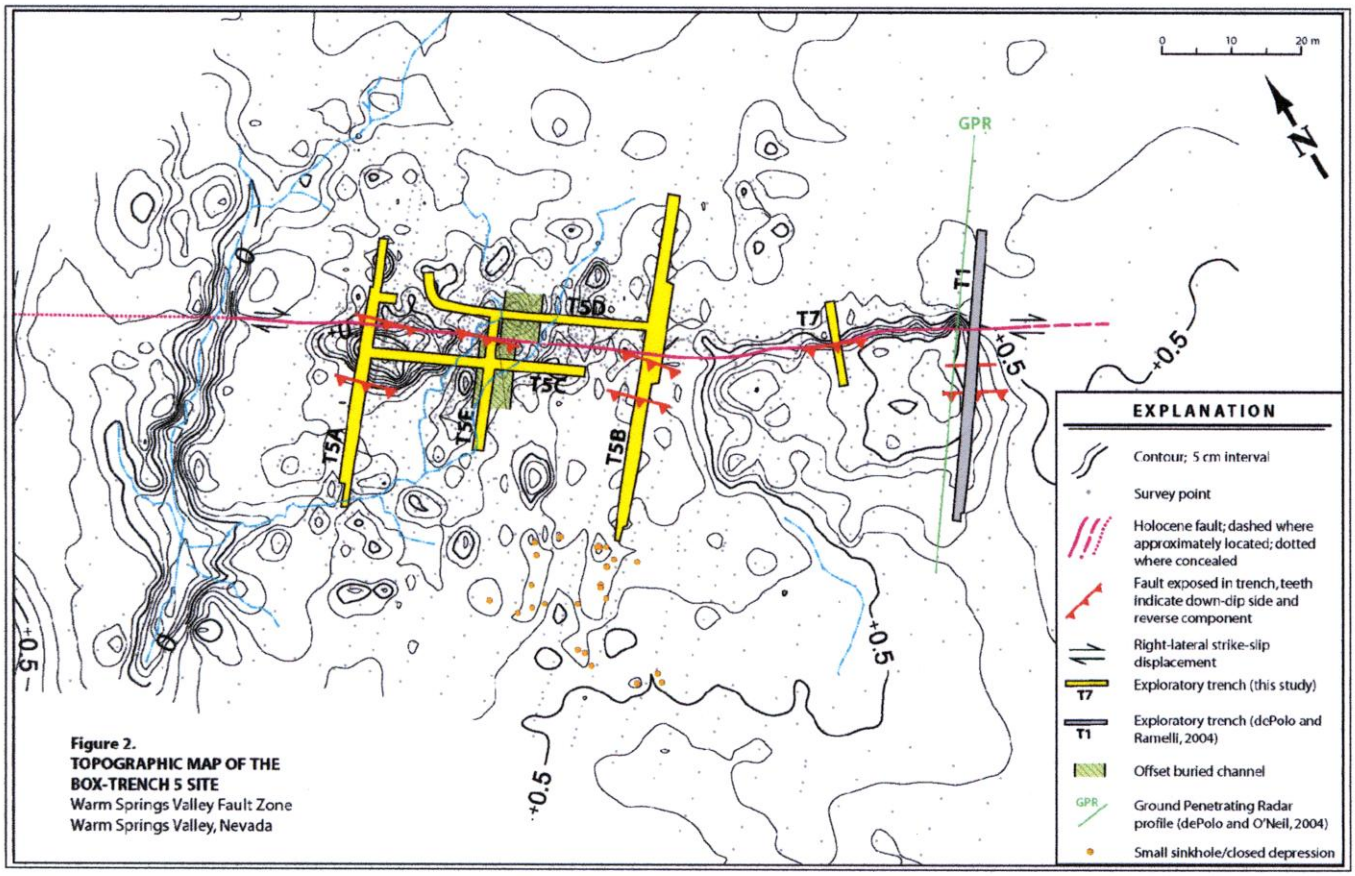
Earthquake History

A paleoearthquake history has been put together for the southern Warm Springs Valley fault system using trenching studies (dePolo and Ramelli, 2004; dePolo, 2006). Direct and indirect evidence indicate as many as eight paleoearthquakes have occurred along the southern part of the system since ~21 ka, but only two events appear to have occurred in the Holocene.

The setting at the Mid-Valley site is a flat basin floor with series of push-up mounds from a few to several meters in size, some with apparent scarplets along their edges. The fault is expressed as vegetation lineaments, the push-up mounds, and very subtle changes and patterns of ponded sediments and the eroding basin floor (dePolo and Ramelli, 2004). Fault traces cross the site with a left-stepping pattern (comparing orientations of faults in the trenches versus the overall fault zone) and are generally perpendicular to the drainages flowing across the valley floor. Recognizing the push up mounds were formed during the high stand of Lake Lahontan, the opportunity for a stream channel to be confined between the mounds, cross perpendicular to the fault, and be subsequently offset was hypothesized. Fortunately the hypothesis was correct, a unique stream channel was found with a box trench, and it was offset by the fault (dePolo, 2006).

The trenches are at the Mid-Valley site within Warm Springs Valley. Deposits exposed include silty and fine sandy basin deposits, sandy channel deposits, lacustrine sands from the recent highstand of Lake Lahontan, and older silts, sands, and clays. Faults, for the most part, were distinct and easy to map in the trenches. Dating the deposits has been difficult, however, with five samples submitted to Paleoresearch Labs looking for charcoal, micro-charcoal, and humates with no luck. There is one bulk radiocarbon date, the highstand deposits that can be correlated to a time, and a photon-stimulated luminescence date to constrain the earthquake chronology.

Most of the paleoseismic history can be deciphered from Trench 1, a trench across the edge of a push-up mound. Four young events are evident on the main fault but the uplifted core of the mound also has evidence for paleoearthquakes. Evidence for the only paleoearthquake not identified in Trench 1 (PE3) is found in the Box Trench Complex (Trench 5). Trench 2 is not shown and is to the left of the lower figure.



Topographic map made by Tom Sawyer of Piedmont GeoSciences.

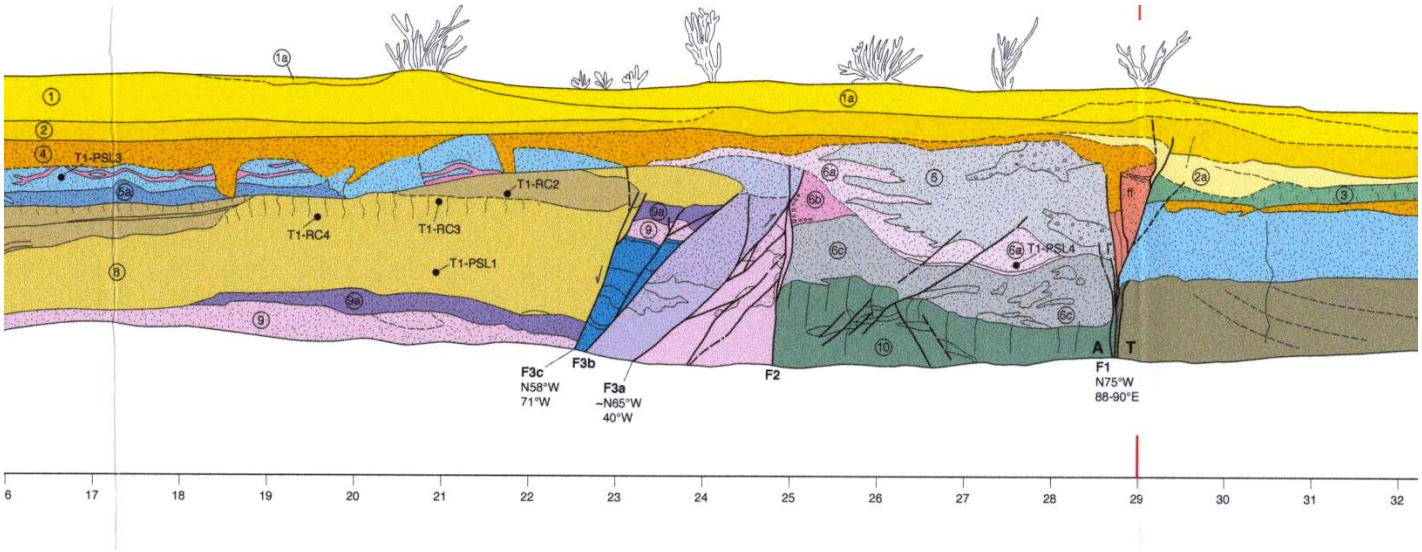
Paleoearthquake History at the Mid-Valley Site of the Warm Springs Valley Fault System

Paleo-earthquakes and Age	**Event Horizon**	**Evidence for Paleoearthquake**	**Estimated Displacement (vert., RL)**	**Basis for Displace. Estimate**	**Style of Deform.**
PE1 latest Holocene	unconf. on unit 1b (T2)	sm. colluv. wedge, upward term. flts. sheared unit 2 deposits	av. - 20 cm (T2)	T2 - offsets meas. from log on F1	RL SS (?)
PE2 early Holocene	upper part unit 3, lower part unit 2 (T1, T5A, T5B)	colluv. wedge, flted. unit 3,	av. - 60 cm (T2); RL - ~1.3 m (T5 complex)	est. scarp height; est. stream chan. offset	NRL OS
PE3 < 15 ka & > 9 ka	unconf. on unit 3b (T5B&D)	liquefaction, ang. unconf.; buttress depo. on scarp; fault silt ejecta.	RL - ~1.3 m	est. stream chan. offset	NRL OS
PE4 ~ 15 ka (highstand)	unconf. on unit 5C, fissure fill (T1)	liquefaction, ang. unconf., fissure fill, tilted block	av. - ~ 50 cm	offset deposits	NRL OS
PE5 < 21 ka & > 15 ka	fissure fill (T1)	fissure fill	???	???	RL SS(?)
PE6 < 21 ka & > 15 ka	buried fault scarp, unconf. within unit 6 (T1)	offset & shrd. deps., colluv. deposits, upward term. flts	av. - ~1.5 m	min. vert. offset of deposits	RRL OS
PE7 < 21 ka & > 15 ka	unconf. on faulted wedge with Unit 8 (T1)	upward term. flt	av. - ~1 to 2 (?) m	~ offset deposits	RRL OS (?)
PE8(?) < 21 ka & > 15 ka	unconf. on top(?) unit 7 (T1)	offset deposit, buttressed Unit 6(?) sm. wedge	av. - 1.5 m	offset deposits	NRL OS

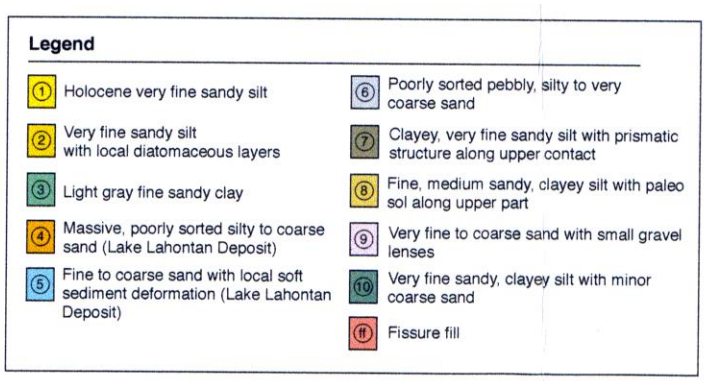
T = trench (T2 – Trench 2); RL SS = right-lateral strike-slip, NRL OS = normal right-lateral oblique-slip, RRL OS = reverse right-lateral oblique-slip, av. = apparent vertical.

Mid-Valley site geologic units

The same geologic units can be found in most of the Mid-Valley trenches. Trench 1 has three general parts; the eastern and western parts each have three general packages of sediments, whereas the central portion is an older uplifted part of the push-up mound and is made up of faulted sands, silts, and muds. The eastern and western parts are made up of older muds in the lower part, overlain by sediments from the highstand of Lake Lahontan, and these in turn are overlain by post-lake, mostly subaerial silts and fine sands. Some important deposits not recognized in Trench 1 are a package of post-Lake Lahontan, subaerial, alternating silts and sands that include the offset channel deposit and evidence of Paleoearthquake 3; these are found in the adjacent low area between mounds and are exposed by the box trench (Trench 5 complex).



Portion of Trench 1 log; scale below in meters with no vertical exaggeration. View of north wall. From dePolo and Ramelli (2004).



Paleoearthquake 1

Evidence for the most recent event includes shearing, small offsets, and possible warping of unit 2 deposits, including faulting of a colluvial deposit related to PE2 (Trenches 1, 2, 7); this is the offset of unit 2a by fault F1 in Trench 1. PE1 is not evident in all trenches, and apparently only had small, discontinuous surface ruptures; in most trenches PE1 offsets appear to die out just below the paleo-surface. Offsets from PE1 in Trench 2 are in very young unit 1 deposits that are among the highest in the section, lack soil development, and are likely latest Holocene, perhaps less than a few thousand years old (but this is unconstrained). A small fault scarp may have formed at Trench 2, which in turn eroded to form a small colluvial(?) deposit, unit 1a. Offsets measured from PE1 were as much as 20 cm apparent vertical (normal?).

Paleoearthquake 2

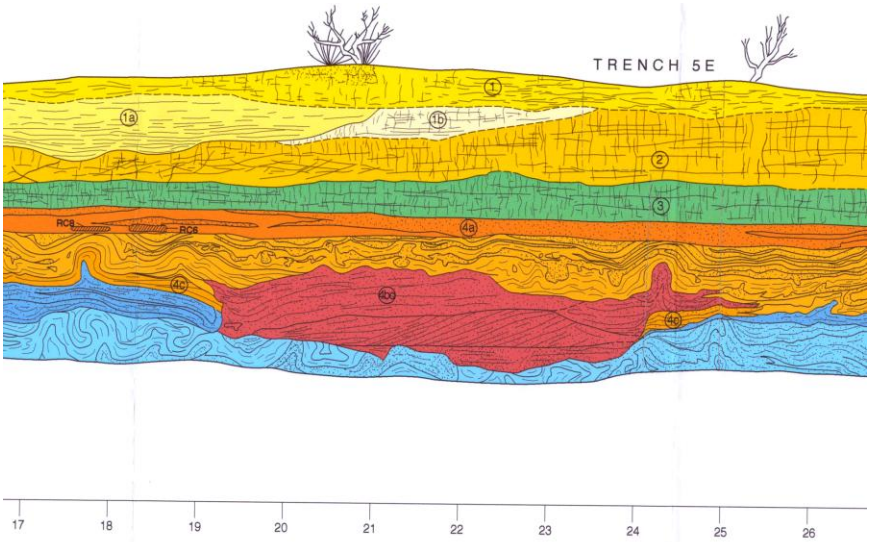
Paleoearthquake 2 is evident in all trenches and created 20- to 60-cm-thick colluvial wedge deposits (indicating fault scarps of similar or larger heights). An example is unit 2a in Trench 1. There appeared to be tilting and warping of the push-up blocks from PE2, consistent with the vertical offsets on their eastern sides (where the main fault traces usually is). Tectonic depressions created by PE2 were wet areas (as indicated by gleying or a greenish reduced-iron color) and were filled with unit 3 and/or lower unit 2. Vertical offsets from PE2 at the Mid-Valley site are both apparent normal and apparent reverse indicating local structural and geologic control.

The box-trench complex exposed offset buried stream channel deposits, shown in the trench site diagram, the portion of Trench 5D log, and the projected channel figure. After mapping the box, an additional trench (T5E) was dug to assure the channel went straight into the fault without meandering or other complications; it is straight. The best estimate of the right lateral offset is 2.5 m (2 - 3.6 m). The channel is younger that Lake Lahontan highstand deposits, but older than the Holocene (based on the radiocarbon date from unit 3). Lateral offset during PE2 is attributed to approximately half of the total right-lateral offset of the stream channel exposed in the box trench, which is ~1.3 m.

PE2 appears to have occurred in early Holocene, because the event horizon is near the top of unit 3 and the lower part of unit 3 has a bulk, conventional radiocarbon date of 9,970 ±550 ^{14}C ybp (lab # GX31502), which dendrocorrects to 9,950 – 12,942 cal ybp (using Stuvier and Reimer, 1993, and Reimer and others, 2004).

Paleoearthquake 3

The evidence for PE3 is mostly indirect or secondary but is reasonable convincing; this is partly because the area was one of erosion, or erosion was induced at the site from the event, so a record was not left at all sites. The event horizon is usually an unconformity (commonly an angular unconformity) on top of contorted (liquefied) deposits. The most



visible evidence for PE3 is liquefaction which gets more contorted and with higher fold amplitudes adjacent to the fault in Trenches 5A, 5B, and 5E. This area appears to have been a subaerial channel that crossed the site and was filled with unit 4, whereas at adjacent trenches (Trenches 1 and 7) were topographically higher and in more erosional settings. In Trench 5E there is a silty injection area in the immediate hanging wall that indicates the main fault acted as a conduit for liquefaction.

Fault-parallel Trench 5D log showing the channel that was offset right laterally by the fault. Note the middle orange colored unit 4 does not correlate with the same number in Trench 1. In the Trench 5 complex trench logs portray the Lake Lahontan sediments as unit 5 (blues; lower lighter blue is pre-PE4 and darker upper blue is post-event). Two episodes of liquefaction are evident with unconformities on top of contorted deposits. The trench wall is approximately 3.5 m high

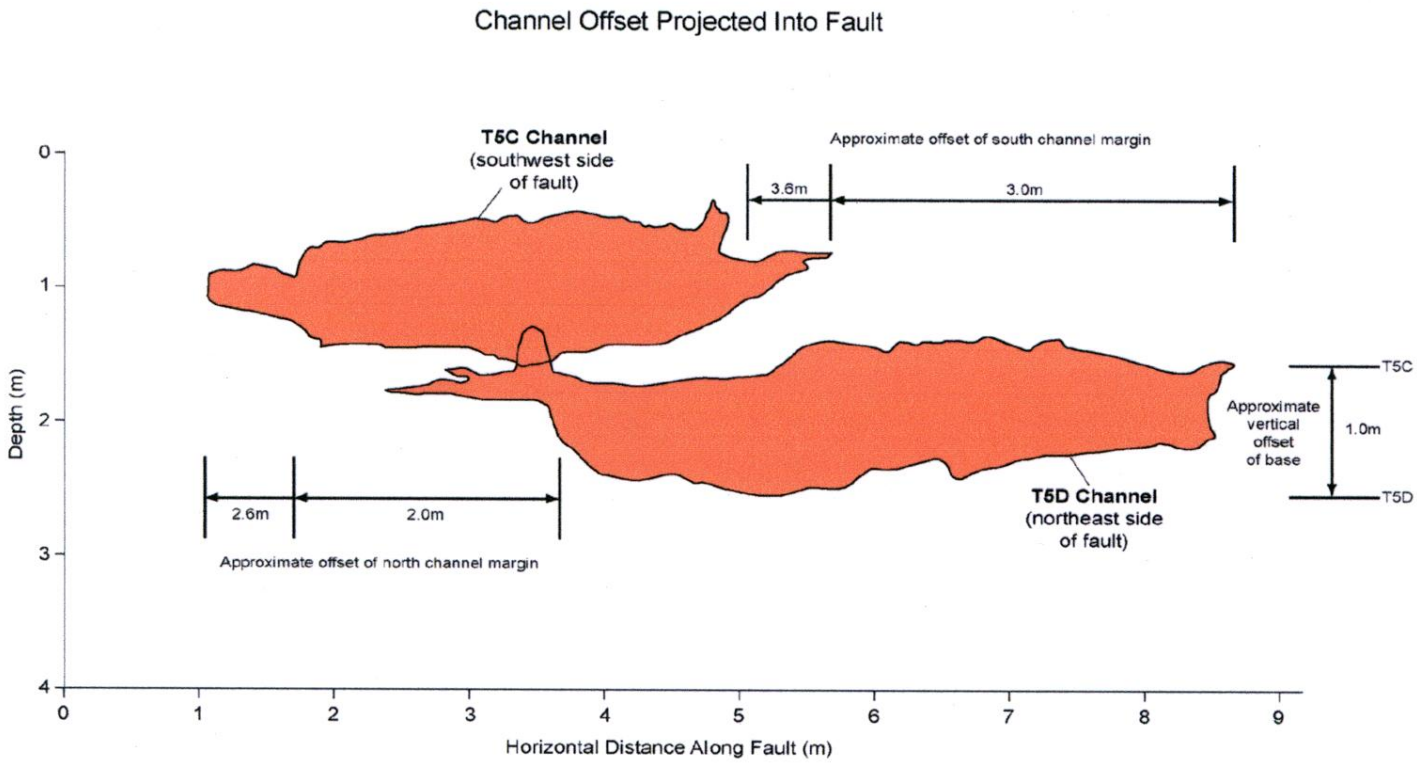


Figure 3. Offset stream channel cross-sections projected into a vertical view at the fault (view to the northeast, across the fault). The fault strike (plane of the paper) is N65°W. Cross-fault distance between the channel exposures is 5.7m. Right-lateral and vertical displacement is indicated by the difference in location of the channel on either side of the fault. Some offset measurement possibilities are indicated; the best estimate of the offset is 2.5±0.5m based on projections of the channel margins into the fault. Vertical offset is 1±0.25m based on this figure.

Figure from dePolo (2006). Note the channel outline is reversed from Trench 5D log. Channel is post-Lake Lahontan highstand.

In Trench 7 there appears to be a tilted angular unconformity on unit 5a, which likely was tilted by PE3 (unit 5a is post-PE4). Unit 4a and unit 3 appear to form tapering, on-lapping contacts as if they were filling against a small uplift of the push-up mound created by PE3.

PE3 occurred between the highstand of Lake Lahontan and the early Holocene deposition of the green, clay-rich deposits of Unit 3, and is latest Pleistocene. Using the radiocarbon date from unit 3 (discussed under PE2) a minimum age of 9,950 ybp is estimated for PE3. Dendrocorrecting bracketing dates of Lake Lahontan's recent highstand from Adams and Wesnousky (1998) gives a maximum bracketing date of the highstand and the event of 15,800 cal ybp. Thus, PE3 occurred between 9,950 and 15,800 ybp.

Paleoearthquake 4 (Lahontan high stand event)

Paleoearthquake 4 occurred during the high stand of latest Pleistocene Lake Lahontan, when the site was potentially under about 44 m of water. This is supported by severe liquefaction, lateral spreading, and dating of lacustrine deposits. Before the earthquake, the site was covered with 80 to 130 cm of well to moderately sorted, moderately stratified, moderately to well-rounded lacustrine sand. During PE4 the push up mound was shaken, uplifted at the fault, and tilted to the west, liquefying and laterally spreading the lacustrine sands to the west, where they froze with contorted, soft-sediment deformation. Severe liquefaction from PE4 has been identified in Trenches 1, 5C, and 5D. A fissure was created at the main fault in Trench 1 and filled with massive lacustrine sand that blanketed the site.

The liquefied sand was dated using photo-stimulated luminescence (PSL) dating at 15,300 ± 4,000 ybp (2 sigma) which is consistent with other dating constraints of the high stand. Adams and Wesnousky (1998) have bracketed the highstand of Lake Lahontan with radiocarbon dates that dendrocorrect between 15,950 and 15,120 cal ybp. Thus, PE4 occurred between 15,120 and 15,950 ybp. A luminescent date from liquefied high-stand sand deposits in Trench 1 was 15.3 ±4 kybp, supporting this age range.

Paleoearthquake 5

A large fissure fill in Trench 1, subsequently fissured by PE4, is the primary evidence for PE5. Other evidence includes truncated faults and down-dropped blocks. This event appears to have occurred prior to the high stand of Lake Lahontan, and included small pieces of an Av horizon formed on an adjacent uplifted block at that time.

There is little age control on PE5, except that it preceded the high stand, and thus is older than 15,120 ybp (see PE4 for high stand age discussion). A luminescent date from liquefied high-stand sand deposits in Trench 1 was 15.3 ±4 kybp.

Paleoearthquake 6

PE6 is recognized on fault splays west of the main fault (faults f2 and f3a in Trench 1; dePolo and Ramelli, 2004), in the uplifted core of the push-up mound. Subaerial sands are faulted and caught up in a wedge (unit 6b) indicating an apparent reverse displacement. Subsequent erosion of a fault scarp created by PE6 created a colluvial/tectonic depression-fill deposit with interfingers of coarser material (unit 6a) that eroded from the top of the fault scarp. These deposits are all older than, and are fissured by, PE5. Apparent reverse displacements during PE6 are 1.5 m; right-lateral displacement is also presumed to have occurred.

There are no specific timing constraints for PE6, except that it is between the oldest date in the trench (~21 ka) and the high stand age (~15.5 ka).

Paleoearthquake 7

A second truncated fault splay in the uplifted block of Trench 1 (fault f3b) is capped by deposits that are in turn faulted by PE6, and thus this truncated splay represents an older event. This event caused 1 to 2 m of apparent reverse displacement and assumed strike-slip motion. PE7 is younger than unit 7, which is dated with PSL at about 21 ±4 ka, and older that PE6.

Paleoearthquake 8(?)

PE8(?) is the most poorly defined event, because of an uncertain capping deposit that is faulted by PE7 in Trench 1 (fault f3c). The uncertainty comes from the possibility that both faults involved in PE7 and PE8(?) moved during the same event (faults f3c and f3b). This does not seem likely, however, because the apparent offsets are large and of opposite apparent motion. Fault f3c has nearly 1.5 m of apparent normal dip-slip displacement, whereas offsets on fault f3b have about the same amount of apparent reverse movement. An earthquake surface rupture that involved both of these faults would slide along one fault in contraction then switch to a second fault splay, change dip-slip motion, and extend and down-drop the geology, which does not seem likely (if this really happened, the same fault trace, or weakness, would likely be used). Even though the faulted capping deposit over the fault with PE8(?) is uncertain, it is probably a separate event and is favored by dePolo and Ramelli (2004) and dePolo (2006); this indicates two separate events, PE7 and PE8. PE8(?) was younger than unit 7, which is PSL dated at about 21.2 ±4.4 ka. The only other constraint on the age of this unit is a bulk AMS radiocarbon date from near the top of the older sediment package, near the surface that was inundated by Lake Lahontan. This is sample T1-RC1 which is dated at 18,990 – 18,770 cal ybp (sample #GX30095), consistent with the PSL date.

Summary

There is evidence for seven or eight paleoearthquakes along the southern Warm Springs Valley fault system since ~21 ka. Of these, six or seven appeared to be substantial events, likely with offsets >1 m right laterally. The most recent event smaller offsets. It should be noted that earlier, similarly small events as PE1 may not be recognized as distinct events on faults that have been overprinted with larger offsets. Thus, more "PE1-type" events might have occurred during the time record.

Fault Slip Rates

There are two fault slip rate estimates for the Warms Springs Valley fault system, a long-term geologic rate and a two-event rate derived from trenching studies.

Long-Term Geologic Rate

An independent long term rate for the WSVFS can be estimated by using a 10 to 15 km right-lateral offset of a well-mapped Miocene river channel deposits (Faulds and others, 2005) and a 3.6 to 6 My time frame for the offset (Henry and others, 2002). This yields a long term, right-lateral rate of 1.7 to 4.2 km/My.

Two-Event Slip Rate

A two-event rate can be estimated from the box trench exploration (dePolo, 2006). This site showed evidence of a buried paleo-channel that is perpendicular to fault, and was offset right laterally about 2.5 m (2 – 3.6 m). The channel is in post Lake Lahontan highstand deposits and the offset is thought to have been created by PE3 and PE2. PE1 is not evident at the channel offset site, so it is assumed that it does not contribute significantly to this offset. PE2 occurred near the end or just following the deposition a distinctive greenish clayey deposit (unit 3) that has a radiocarbon date from the base of 9,950 – 12,940 cal ybp (dePolo, 2006). The accumulation time for PE3 and PE2 is the time after PE4, which occurred during the highstand, minus the time since PE2. The range in the time of the high stand is 15,120 – 15,950 cal ybp (Adams and Wesnousky, 1998), and a range in estimated time since PE2 is 12,940 years to an estimated minimum of ~5,000 years. The change from wetter to drier conditions is indicated in the geology (gleyed to oxidized), and is interpreted to be the approximate beginning of Holocene (11,500 cal ybp); PE2 appears to have occurred very close to this change, thus, a preferred age of 11.5 ka is adopted for PE2 (this is also the approximate midpoint of the radiocarbon age range). Dividing the preferred and range of offset values by the preferred and range of accumulation times gives a preferred fault slip rate of 0.63 m/ky, (0.19 – 1.65 m/ky), or rounded, 0.6 m/ky (0.2 – 1.7 m/ky).

Earthquake Recurrence Intervals

Along the southern portion of the WSVFS earthquakes have had variable interseismic intervals, which have recently appeared to increase in time (inter-cluster period?). Another way of viewing this is to say we had a cluster of earthquakes in latest Pleistocene and only one or two events in Holocene (fig. 4). With relatively high rates of geodetic strain in the western Great Basin over this fault, it seems unlikely the fault system has slowed down significantly over such a short time period. It is more likely that a large earthquake, or series of earthquakes, along the WSVFS is geologically imminent.

This variation in earthquake occurrence can be illustrated by viewing the latest Pleistocene and Holocene periods. The bounding age ranges are 18 to 25 ka for the entire paleoseismic record based on the lower luminescence date in Trench 1 (T1-PSL1), and the 10 to 13 ka bulk radiocarbon date for the green clay-rich unit in the middle of the

Paleoearthquake History of the Warm Springs Valley Fault System at the Mid-Valley Site

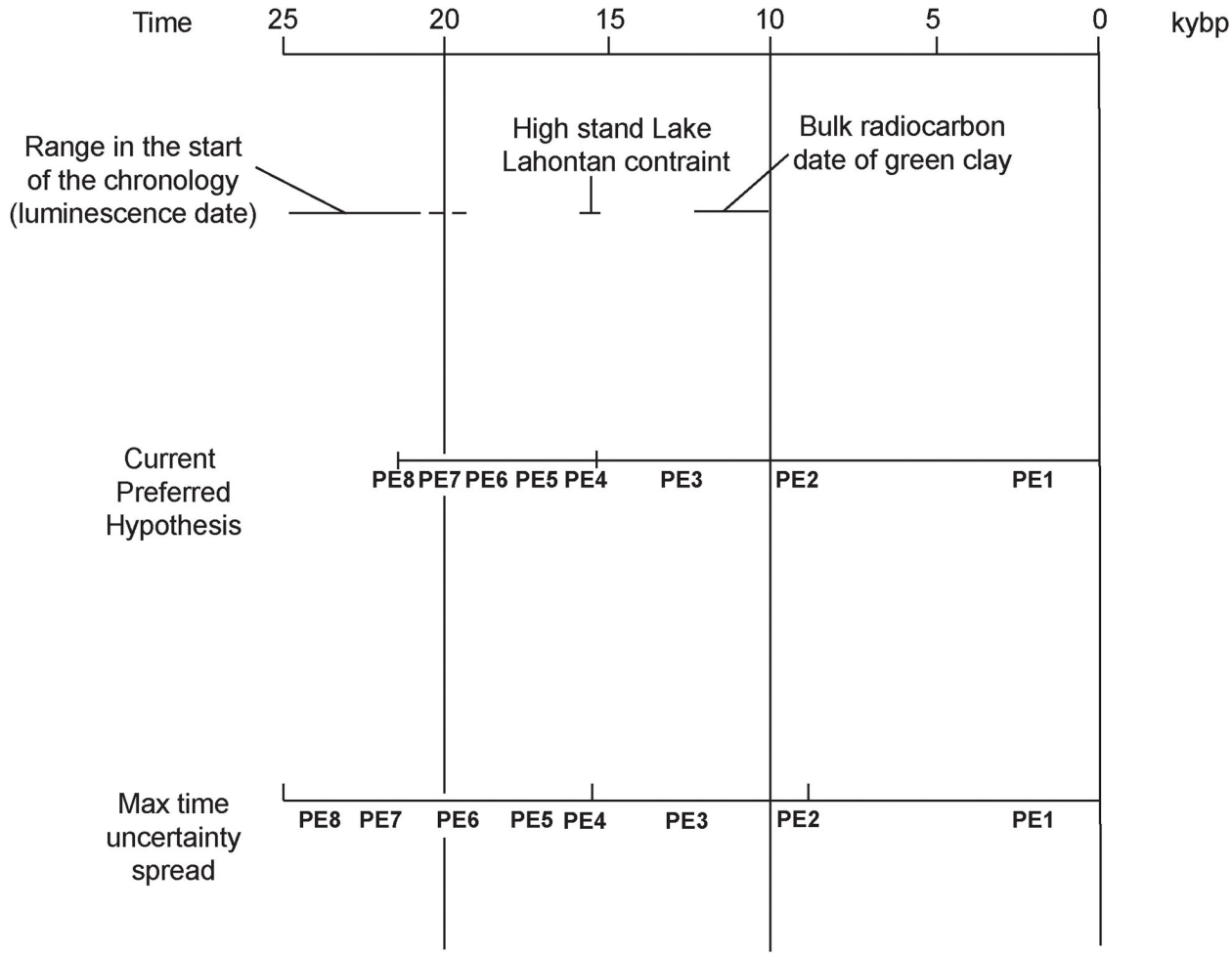


Figure 4. Two examples of the possible paleoearthquake history of the WSVFS at the Mid-Valley site. PE4 occurs during the high stand of Lake Lahontan and is an important constraint. A cluster of earthquakes occrred in latest Pleistocene, whereas a relatively low level of activity occurred in the Holocene.

record, or near the start of Holocene. Using the maximums and minimums of the dates, the oldest time period (~21 to ~11.5 ka) could be 5 k to 15 ky in duration (best estimate is 21 – 11.5 = 9.5 ky). Five to six earthquakes occurred in the oldest time period (preferred is six) and one to two occurred during the youngest time period, ~11.5 ka to present (10 to 13 ky in duration). In the youngest period two events could be placed such that they divide the 10 ky duration into thirds (~3 ky), or an event can be placed at either end of the longest possible duration, 13 ky.

Using these data an average earthquake recurrence interval over the period of ~21 to ~11.5 ka was 1.6 ky (0.8 - 3 ky). Considering different ways the events could be placed in the younger period gives an approximate interseismic interval range of 3 - 13 ky, with a "preferred" value of 6 ky. There isn't a lot of overlap in the ranges between these two time periods, no matter what the precise numbers are, there are not as many events in the last 10,000 years as there were in the age range of ~21 to 10 ka.

Another aspect in considering the likelihood that the Warm Springs Valley fault system might have an earthquake is that the most recent event was a very small event in the trenches with discontinuous, small offsets that were significantly smaller than displacements from other events. Thus, it may have been limited in extent, rupturing only a portion of the fault system.

Ignoring the apparent behavior of the fault the total time period of closed interseismic intervals is 12 to 24 ky (removing the current open interval of an estimated 1-4 ky for the occurrence of PE1, and estimated 0 to 2 ky for the open interval on the oldest end of the range, and using 18 to 25 ka for the start of the record and the assumed occurrence of the earliest event. Seven to eight paleoearthquakes are thought to have occurred during the closed interval estimate of 12 to 24 ky. Thus, the average earthquake recurrence interval for the southern Warm Springs Valley fault zone over the last 18 to 25 ka is 1.7 to 4 ky.

Earthquake Segmentation

The length of the Warms Springs Valley fault system, 54 to 96 km, raises the question of the system failing in segments during earthquakes, versus rupturing in its entirety. But segmenting the Warm Springs Valley fault system is challenging because of its relative continuity. More detailed paleoseismic data is needed to document any earthquake segmentation scenarios. The largest "step" in the system is the pull-apart basin in the Virginia Range section, but this feature can be bypassed on the western side by late Quaternary faults. Nevertheless, it is near a half-length of the system, which may be the next best alternative. There is also the slight bend in the fault at its approximate mid-point. Considering the pull-apart basin and the bend in the fault, dePolo (2006) approximated a northern structural segment that is 50 to 57 km long and a southern structural segment that is 38 to 46 km long. More data are needed to define earthquake segments along the Warm Springs Valley fault system. Earthquakes in the Basin and Range Province, such as the 1872 Owens Valley earthquake, have ruptured distances equivalent or greater than the total length of the Warm Springs Valley fault system (cf., dePolo and others, 1991), so a total-length rupture cannot be entirely ruled out.

Single-Event Displacements

The only estimate of single-event displacement for the Warm Springs Valley fault system is from the offset stream channel found in the box trench complex at the Mid-Valley site (dePolo, 2006). The channel is offset 2.5 m (2 – 3.6 m) right laterally. This likely

occurred during two events (PE2 and PE3) and thus with no other information available, these values are halved between the events, assuming the offsets per event were the same. This gives a single-event displacement estimate of 1.3 m (1 – 1.8 m) right-lateral. This site is along the southern reach of the fault system, and single-event displacements are likely larger to the north, at more central locations of the system. At this trench site there is not evidence for offset from PE1, so it is assumed to not be a significant source of uncertainty in the number of events offsetting the channel.

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Nevada Quaternary Fault Working Group **<u>Las Vegas Valley fault system</u>**
FAULT FORM

Cashman Field fault

Fault Name

Las Vegas Valley fault system
USGS Fault and Fold Database
Fault #1120

Decatur fault
Valley View fault
Cashman Field fault
Whitney Mesa fault
Eglington fault
West Charleston fault

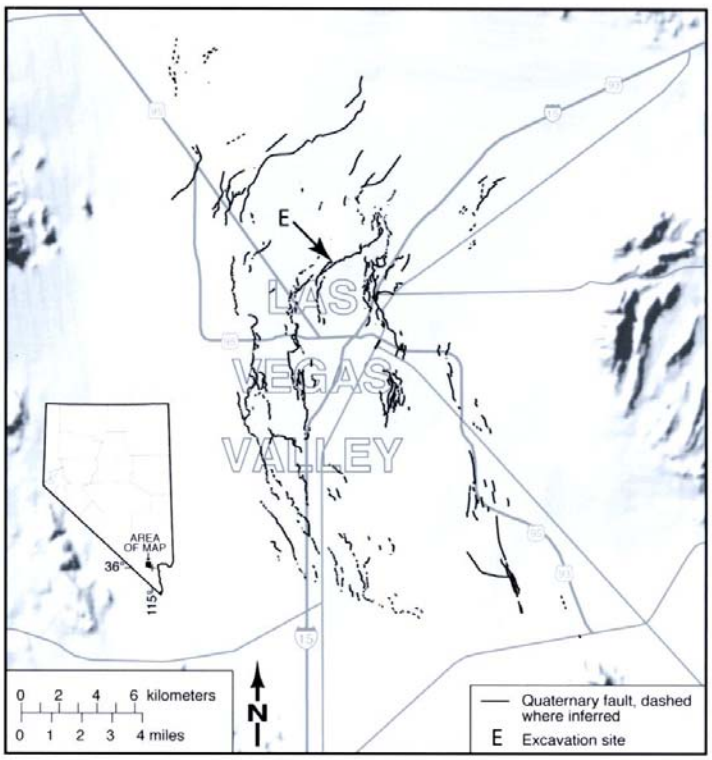
The Las Vegas Valley fault system was named by Wyman and others (1993), and the specific names of the faults were given by Slemmons and others (2001) and were first labeled on a geologic map by Page and others (2005). Originally the fault scarps were referred to as Scarp I (Decatur fault), Scarp II (Valley View fault), Scarp III (Cashman Field fault), and Scarp IV (Whitney Mesa fault) by Conwell (1965).

The individual faults are briefly described here, except the Eglington fault, which has its own separate report.

Introduction, Location, and Length

The Las Vegas Valley fault system is an ultimate earthquake conundrum representing low probability hazard and extremely high exposure consequences. This is because the tectonic capability of the system has been considered uncertain. The fault system is located in central Las Vegas Valley, southern Nevada, home of 1.8 million people. An earthquake from the Las Vegas Valley fault system threatens Nevada's largest city with near-field ground motion and surface ruptures, as well as collateral effects, such as liquefaction. HAZUS computer simulations of Las Vegas indicate that even a moderate earthquake within the basin is a probable disaster.

The best outcome for Las Vegas and Nevada is that the scarps were totally created by hydrocompaction, or some other non-tectonic process, and that there is no specific earthquake threat directly under the city. The worst-case scenario occurs if the faults are assumed to be non-tectonic but are actually seismogenic and earthquake forces are greater than designed for. In this case, Las Vegas could suffer catastrophic losses that might be prevented with better fault characterization.



Quaternary faults in Las Vegas Valley

Figure 1

Major Fault Reports (in chronological order)

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Description of the fault system and scarps

The Las Vegas Valley fault system was initially mapped by Maxey and Jameson (1948), and has been mapped at a scale of 1:24,000 (Bingler, 1977; Matti and Bachhuber, 1985; Matti and others, 1987; Matti and others, 1993; McDonnell-Canan and others, 2000). The system is 30 km long, 11 km wide, and has an overall trend of ~N20ºW. The fault system is located in the central part of Las Vegas Valley and can be divided into five principal fault zones. These fault zones appear to be normal dip-slip faults, and are ubiquitously down-to-the east or southeast. The faults are expressed as 10- to 40-m-high fault scarps, fault-line scarps, warps, springs, and vegetation and tonal lineaments.

The system has been described as arcuate in shape, but in detail, this isn't quite accurate. There are three sub-patterns within the system, a northern northeast-striking section, a central more northerly striking section, and a southwestern or western part that has northwest-striking faults. The northern section is in the area of the deepest part of the basin (c.f., Langenheim and others, 2001) and has the highest fault scarps, some of the youngest fault activity, and possibly the highest fault slip rates. The central section is associated with the piedmont-basin boundary along western side of the Las Vegas Valley, which is not detectible at the surface except for the Quaternary fault scarps (piedmont ~<0.6 km thick alluvium, basin ~>1 km deep). Other northerly striking faults in the eastern part of this section appear to be associated with subsurface structures within the basin (Langenheim and others, 2001). The southwestern part of the system is on the piedmont side of the piedmont-basin boundary, but is subparallel this boundary (Langenheim and others, 2001). It is uncertain whether there are any implications of strike-slip motion because of the northwesterly strike of these southern faults.

Decatur fault

The Decatur fault is the westernmost of the Las Vegas Valley fault system and is a down-to-the-east normal fault with fault scarps as much as 12 m high (Slemmons and others, 2001). The fault commonly forms a ~1-km-wide zone made up of two or more fault traces that strike north-northwest, except for the northernmost end, where they swing northeast, and the southern part, where faults strike N30-35ºW.

The Decatur fault has been proposed to structurally connected to the Eglington fault at its northern end (Slemmons and others, 2001; this is discussed more in the segmentation section of the Eglington fault report). At its southern end the fault appears to merge with, or become indistinguishable from, the Valley View fault. The Decatur fault has an end-to-end distance of ~22 km; Slemmons and others (2001) report 20-25 km for a length.

The Decatur fault likely coincides with a Tertiary fault that forms the west side of Las Vegas basin and today occupies a position between the piedmont and the intermediate-depth basin (Langenheim and others, 2001). It has been portrayed as being the boundary between gravel

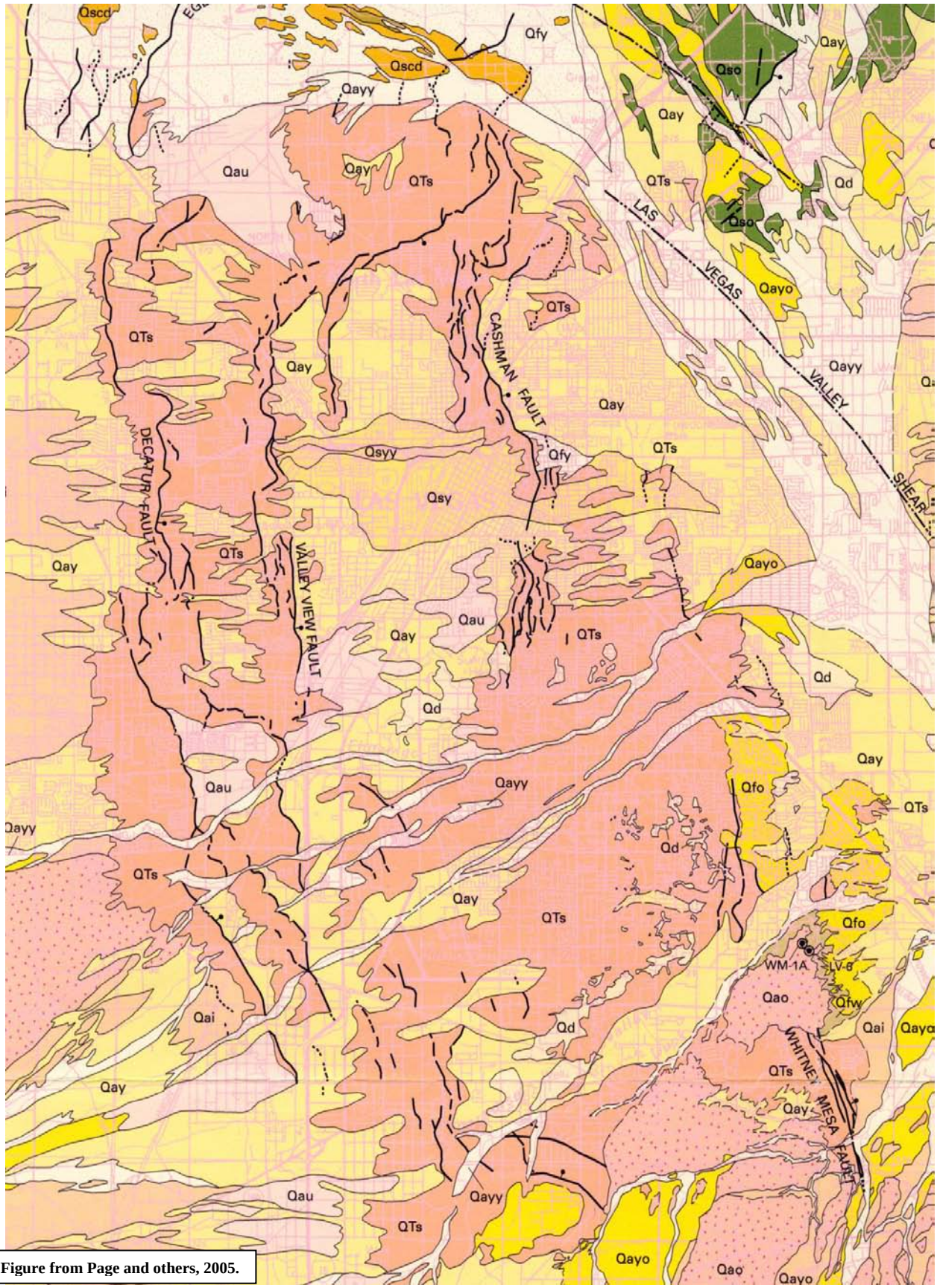


Figure from Page and others, 2005.

dominated deposits and sandy gravel deposits in a cross section originally drawn by Maxey and Jameson (1948), but more recently this sedimentation contrast has been pushed further east, closer to the Valley View fault, and the Decatur is thought to cross mostly coarse-grained deposits (Bell, 1981, commenting on scarp I and see his figures 7 and 8 for sand-gravel percentage distributions in the upper ~200 m of sediments; Wyman and others, 1993, cross section). This limits the amount of compaction that should be considered as forming the Decatur scarps.

Valley View fault

The Valley View fault is the second to the west in the system and is the conduit for the famous Las Vegas Springs. The fault lies about 2 to 3 km east of the Decatur fault, and appears to merge with it to the south. The Valley View fault is a down-to-the-east normal fault with fault scarps up to 25 m high along its northern, northeast-striking part, but heights of ≤10 m for much of the rest of the fault (Slemmons and others, 2001). It is made up of one to a few fault traces and has a N5ºW strike along its central section, swings to a N60ºE strike over its northern reach, and likely merges to faults in the south that strike N30-35ºW. One major fault splay comes southward from the northeast-striking part, near the corner of the Valley View fault, and extends into the hanging wall about 2.5 km (Matti and others, 1987).

The end-to-end distance of the Valley View fault is ~22 km from the northern end, southward to the Decatur fault. The fault is fairly continuous for end-to-end distance of at least 17 km, and a maximum length of ~26 can be measured from fault traces on Page and others (2005). Slemmons and others (2001) reported a length of 27 km for the Valley View fault with a maximum of 31 km if a ruptured continued to the north intersecting the Eglington fault.

Structurally, the Valley View fault is possibly related to an extension antiform on the bottom of the basin that ramps up towards the south, and/or a step in the western side of the basin (Langenheim and others, 2001). Maxey and Jameson (1948) identified the Valley View fault as one that overlies a vertical facies boundary between coarser fan sediments and finer-grained basin sediments, and may have been formed by differences in sediment hydrocompaction. Large portions of the central part of the Valley View fault form the boundary between older and younger alluvium (Matti and others, 1987; Page and others, 2005); thus movement on this fault appears to be controlling the location of contemporary deposition. Faults are also shown within younger alluvium, especially at the change in strike near the northern part, by Matti and others (1987), although this is not portrayed in Page and others (2005).

Cashman Field fault

The Cashman Field fault has a central position in the Las Vegas basin and comes directly southward from a bend in the Valley View fault. The fault crosses the eastern parts of the cities of Las Vegas and North Las Vegas. The Cashman Field fault has fault scarps as much as 40 m high (Mifflin, 1998), which are some of the highest fault scarps in the

valley; this escarpment is surprisingly undissected for its height. The fault is a down-to-the-east and down-to-the-southeast normal fault that is made up of several subparallel traces over a width of 1 to 2 km (Matti and others, 1987). The Cashman Field fault has a north-south general orientation, although locally fault traces have northwest and northeast strikes and have many small curves (Matti and others, 1987). Slemmons and others (2001) connect this fault to the Whitney Mesa fault for a total length of 30 km, but the activity of the Cashman Field fault and the Whitney Mesa appear to be different. The end-to-end length of the mapped Cashman Field fault is ~12 km, with a potential extension to the north increasing this to ~15 km.

The cross-strike distance between the Cashman Field and Valley View faults is about 3 km. The area between these faults appears to be gently tilted westward based on observations of the surface from aerial photography and sedimentation patterns (younger sediments are ponded along the Valley View fault, whereas they pass through the Cashman Field escarpment between older deposits).

A small extension of the deepest part of the basin comes close to the Cashman Field fault on its hanging wall, and the rest of the fault is within the intermediate depth basin (Langenheim and others, 2001). Matti and others (1987) showed the fault as bounding and extending into younger alluvium, whereas, Page and others (2005) only showed faults as bounding young alluvium.

Whitney Mesa fault zone

The Whitney Mesa fault zone is the easternmost fault of the Las Vegas Valley fault system and is made up of a series of discontinuous faults formed in early- to mid-Pleistocene alluvium (Bingler, 1977; Page and others, 2005). The fault zone is a down-to-the-east normal fault with a overall trend of N17ºW and has fault scarps as much as 55 m high (composite height) to the south of Whitney Mesa (Page and others, 2005). The fault zone is made up of three, 3-4 km long fault zones, with burial or erosional gaps between them (Bingler, 1977; Matti and others, 1993; Page and others, 2005). The total end-to-end length of the Whitney Mesa fault zone is about 16 km.

The Whitney Mesa fault zone is puzzling because the southern end, which was quite pronounced with vegetation lineaments and topographic steps, trends into Whitney Mesa, which is capped by middle Pleistocene alluvium that does not appear to be offset very much, if any, by the fault (Bingler, 1977; Bell, 1981). Bell (1981) attributed the scarp-like nature to faults south of Whitney Mesa to resistant petrocalcic deposits 1 m thick, which act as resistant ledges, and called them “resequent” or fault-line scarps. Page and others (2005) did U-series dating of travertine filled fractures aligned with the fault zone in Whitney Mesa with got ages of 363 ±30 ka and 317 ±19 ka. Some short faults of the zone to the north of Whitney Mesa are shown as concealed by late Pleistocene alluvium by Bingler (1977) supporting an older age for activity. Thus, the Whitney Mesa fault zone is one of the lower activity faults within Las Vegas Valley. An exception to this might be the northernmost fault zone that comes within 2 km of the Cashman Field fault (Matti and others, 1993). This fault is shown in places by Matti and others (1993) as

being within intermittently active, or late Pleistocene alluvium.

Eglington fault

The Eglington fault is discussed in a separate report.

West Charleston fault

The West Charleston fault was first identified by Dohrenwend and others (1991) as a series of short, late Pleistocene fault scarps and fault-related lineaments in the western piedmont of Las Vegas Valley. The fault was mapped at a scale of 1:24,000 by McDonnell-Canan and others (2000), and is largely built over today by houses. McDonnell-Canon and others (2000) mapped a zone of lineaments and a couple of back-facing fault scarps in three different ages of alluvium ranging in age from Plio-Pleistocene to late Pleistocene. This zone of faults is about 5.5 km long, ~0.5 km wide in places, and strikes about N12ºE. Page and others (2005) do not show the West Charleston fault on their map but do show a down-to-the-east fault scarp in middle to late Pleistocene alluvium to the southeast of the fault.

The fault offsets Pleistocene alluvial surfaces less than 90 cm, down-to-the-west, although minor alternating of downthrown sides might indicate some strike-slip motion (dePolo, 1993, unpub. fieldwork). The scarp is highly eroded and exists as a small swale in the deposits, possibly formed from a small graben. In adjacent stream cuts small carbonate-filled fractures were found in a zone 1 to 10 cm wide that coincides with the landforms (dePolo, 1993, unpub. fieldwork). The West Charleston fault is real, forms very subtle fault scarps in early to late Pleistocene deposits, and is evidence of some tectonic activity in the eastern piedmont of Las Vegas Valley. Nevertheless, latest Quaternary activity along the fault appears to be absent because strath terraces (on carbonate-cemented alluvium) within drainages between the fault features did not appear to be offset (dePolo, 1993, unpub. fieldwork). In fact, the observations can be explained by having one, or just a few paleoearthquakes in Quaternary. The West Charleston fault crosses gravelly alluvium and local hydrocompaction to form these features is extremely unlikely.

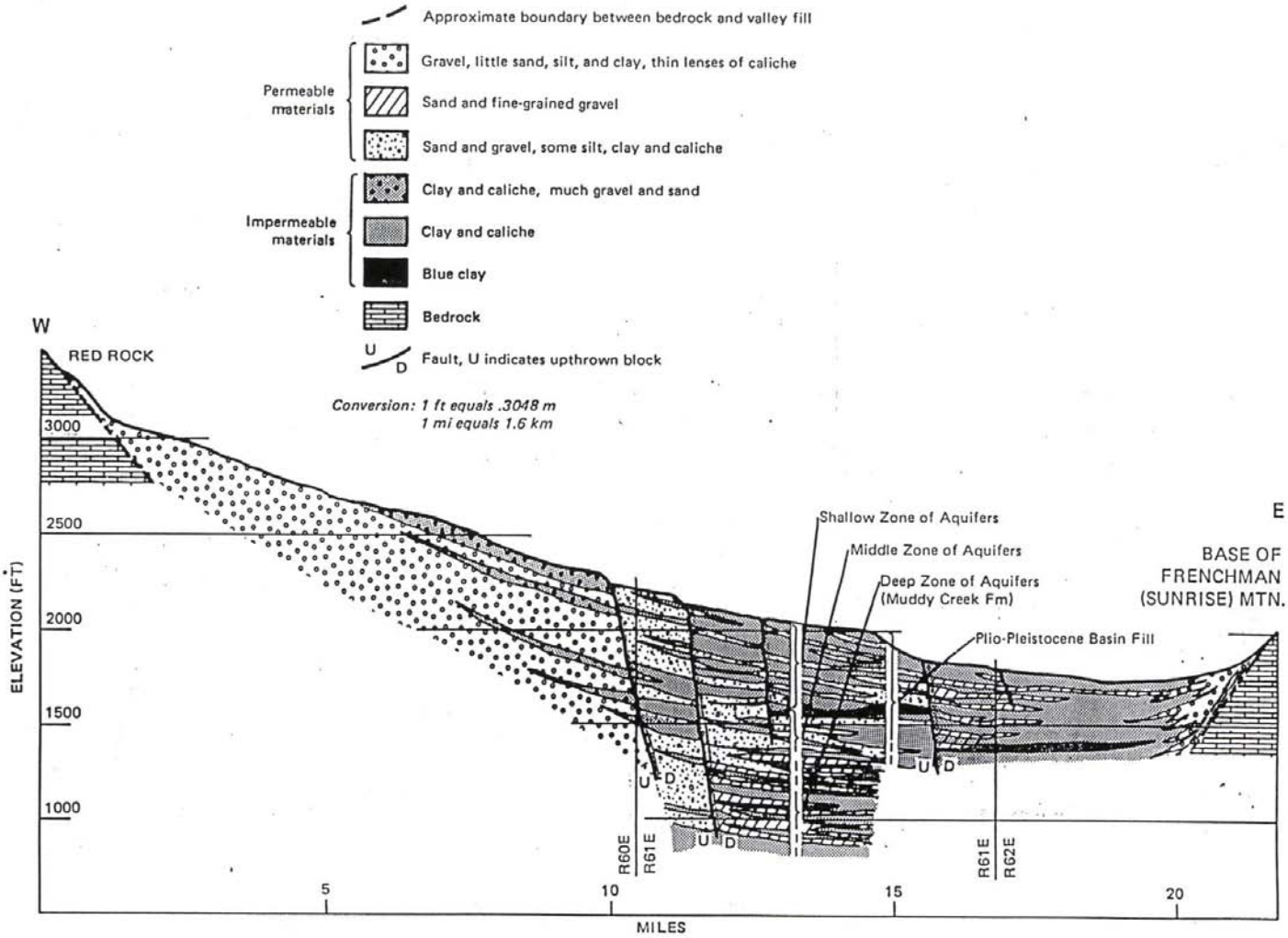
Origin of Quaternary Scarps within Las Vegas Valley

The origin of the Quaternary scarps within Las Vegas Valley has been debated for a few decades now. An early paper by Maxey and Jameson (1948) called upon a non-tectonic, hydrocompaction hypothesis for the origin of the scarps, and that was considered the preferred hypothesis for several decades. This meant that paleoseismic studies were not considered needed and the fault scarps have been largely graded and built over without exploration. The Las Vegas area, especially around the scarps, is subject to the formation of earth fissures and this has limited building on the scarps (c.f., Price and Bell, 1991).

Non-Tectonic Hypotheses

At the 1997 Seismic Hazards of Southern Nevada Conference, Mifflin (1998) made the most detailed non-tectonic case for the scarps that exists. Mifflin (1998) laid out three non-tectonic hypotheses. These were: hydrocompaction, dissolution, and fluvial erosion. A hypothesis Mifflin didn't mention that has been proposed as well, but has generally been discarded, is that these scarps are shoreline strandlines (Price, 1966).

The most popular non-tectonic hypothesis is hydrocompaction. Hydrocompaction was proposed by Maxey and Jameson (1948) who noted that some of the fault scarps were near vertical facies contrasts between the coarser alluvial piedmont deposits and the finer grained basin fill deposits. The basin fill deposits could collapse during dewatering, whereas compaction in gravel laden materials would be less. The scarps would be located near the facies contrast in this model and associated faults would be unrooted, and die out within the basin.



Schematic cross section from a unpublished, 1992, guidebook by Dr. Slemmons, and is modified from Maxey and Jameson (1948).

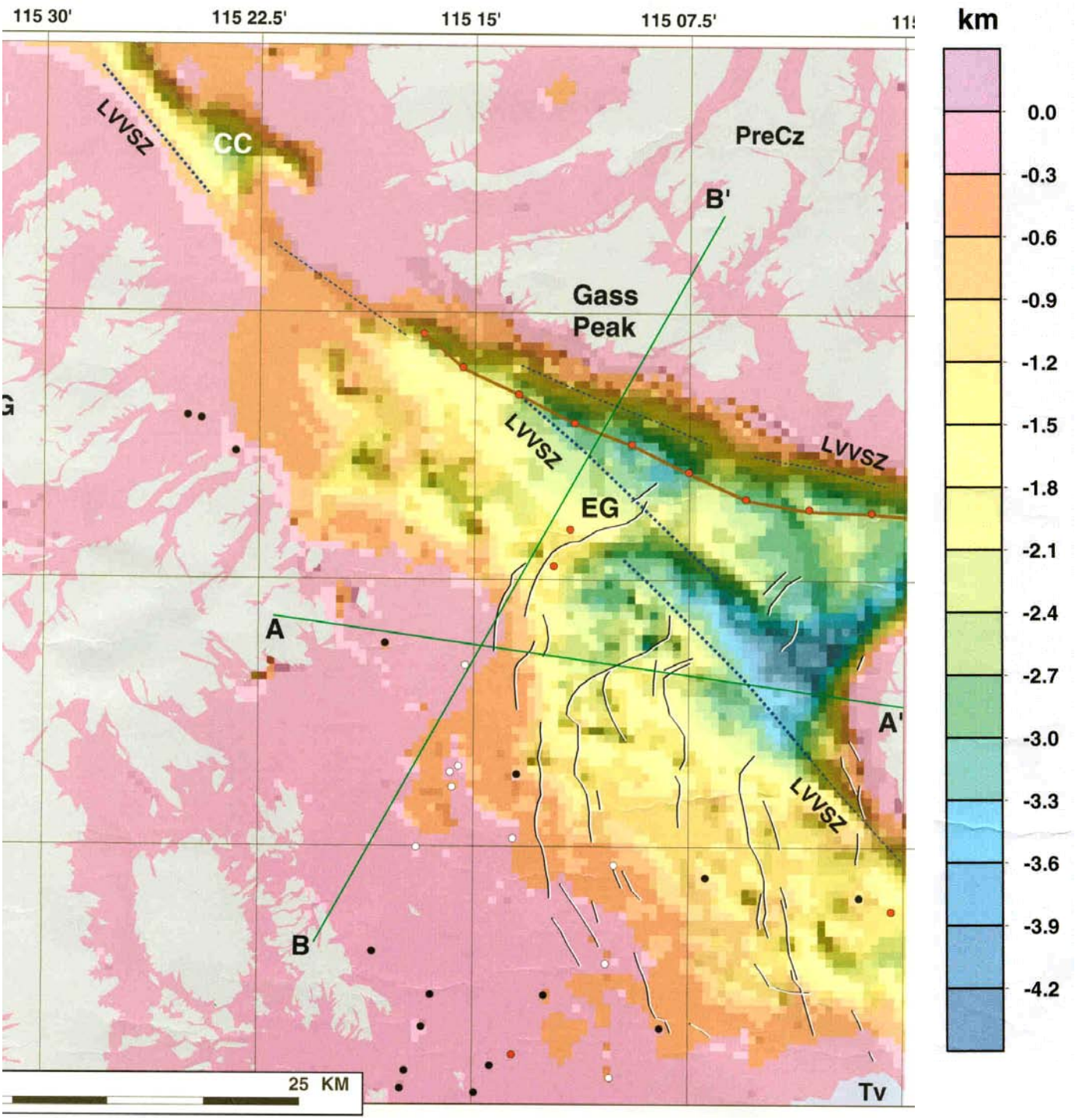
The strongest counter to the compaction hypothesis is the doubt of enough pore water pressure declines to allow the amount of differential compaction needed to form the scarps (Domenico and Mifflin, 1965; Domenico snd others, 1966; Mindling, 1971; Bell, 1981). This argument is summarized well by Bell (1981):

> "The most compelling argument against a differential compaction origin is that extremely large artesian pressure declines would have had to occur to account for the large observed displacements. As calculated by Mindling (1971) about 6 m (20 ft) of artesian-head decline would be required to bring about 0.3 m (1 ft) of land subsidence (consolidation). Thus, an artesian-head decline of at least 600 m (2000 ft) would be necessary to induce the 30 m (100 ft) of differential compaction reflected by some faults. Malmberg (1964) also measured local ratios of subsidence to artesian-pressure decline but concluded that the ratio was more on the order of 1:8. Even so, this ratio would require at least 240 m (800 ft) of head decline to produce 30 m (100 ft) of compaction. Head declines of such magnitude are extremely unlikely based on the geologic and hydrologic history of the basin."

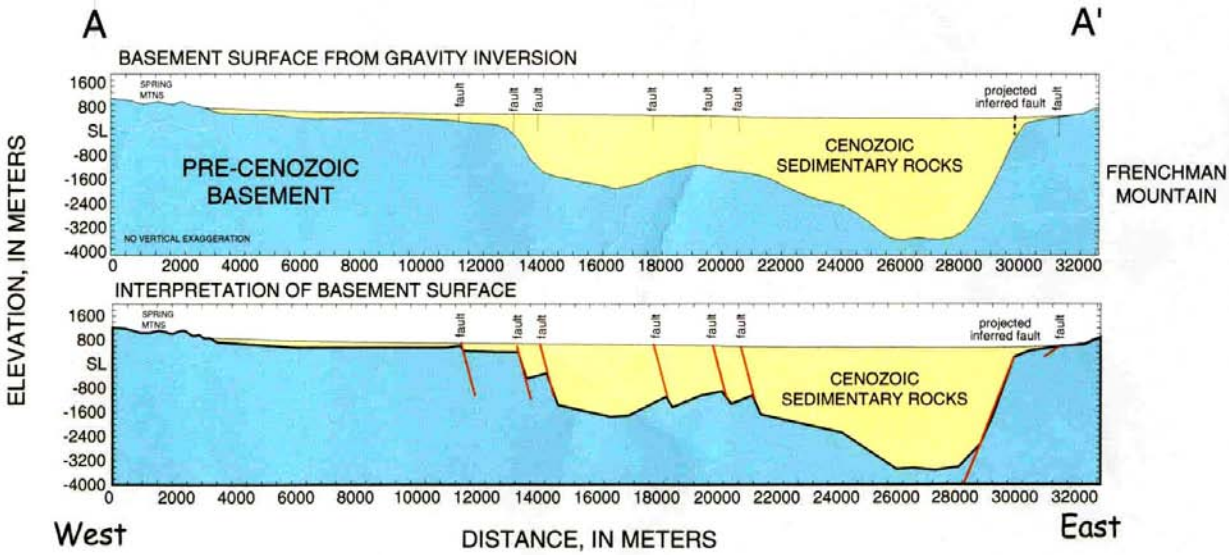
Bell (1981) commented that, "evidence for the existence of a 240-600 m (800-2000 ft) deep lake, which could have induced such large effective stress increases, is lacking." This seems like an extreme statement, until one thinks about what the pre-pumping groundwater conditions in Las Vegas Valley were. There was a shallow groundwater system with artesian flow in the basin (Bell, 1981). This is supposed to be a dry time when the water level is relatively low. With a compaction hypothesis, the Eglington scarp would have been formed in mostly post pluvial conditions, yet high groundwater conditions still existed up till recently.

Water level changes between glacial and interglacial periods are thought to be <100 m in southern Nevada (Quade and others, 1995). Thus, the compaction hypothesis alone cannot explain the fault scarps in their entirety. For faults that lack facies contrasts, it is not really even a possible hypothesis. One of Mifflin's (1998) predictions for defining a compaction origin, that the faults would be rootless, does not seem to be holding with increasing collection of subsurface imagery.

Another perspective on the efficacy of compaction to create scarps is historical subsidence in Las Vegas. Historical subsidence indicates compaction can occur in Las Vegas Valley, although this is likely occurring at artificially rapid rates, and not create any surface breakage along the scarps even though some differential deformation is localizing near them (Varnum, 1987; Bell and others, 2002). Varnum (1987) commented that the subsidence deformation (on the order of ~30 cm vertical deformation measured on short leveling lines across the fault scarps) is being accommodated by extension and warping over large areas rather than rupturing the faults (the depth of the groundwater pumping is generally 200 to 300 m; Bell and others, 2002).



Basin depths estimated by Langenheim and others (2001) based on gravity and drilling data. The Las Vegas Valley faults are shown (EG is the Eglington fault) as is the deeper Las Vegas Valley shear zone. The deeper part of the basin is blue and green (darker) and the yellows are the intermediate depth basin.



Cross section AA' from Langenheim and others (2001).

The dissolution hypothesis consists of dissolving carbonate rocks and calcic deposits and removing them with the groundwater (Mifflin, 1998). Additionally some local buried deposits, such as the Muddy Creek formation, have intercalated gypsum and salt beds that could be subjected to dissolution, removal, and collapse. No follow up work has been done on this hypothesis and it is considered to be a possible contributing factor to subsidence of unknown importance. As an additional note, Longwell (1936) commented that there is some salt tectonics activating faults in the Lake Mead area, but this has never been directly extended to the Las Vegas basin.

The fluvial erosion hypothesis was forwarded by Mifflin (1998) principally for the eastern Whitney Mesa escarpment, which does not have a fault associated with it (Bell, 1981). Fluvial erosion and general slope retreat appears to be likely hypotheses for the formation of this escarpment.

Tectonic Hypothesis

The tectonic hypothesis for the origin of the scarps has been proposed for four decades now, and appears to have local support among the consulting community, but proving the tectonic/earthquake model is difficult. Mindling (1964), Haynes (1967), Bell (1979), and Bell (1981) were the earliest to suggest that the scarps within Las Vegas Valley may be tectonic in nature. More recently, an earthquake origin has been argued by Bell and dePolo (1998), Slemmons and others (2001), dePolo and Taylor (2005), and dePolo and others (2006). The argument for an earthquake origin to the fault scarps has largely been the consideration of a suite of factors that tend to support the tectonic/earthquake hypothesis:

Factors that indicate the fault scarps are tectonic:

- Basin floor bedrock fault offsets below fault scarps (Plume, 1984; Langenheim and others, 2001; Snelson and others, 2004 & 2005),
- Major fault control of Quaternary sedimentation within the basin (Matti and others, 1981; Taylor, 2005, unpublished research),
- Similarity of fault orientations and patterns with regional tectonic faults (Bell, 1979 and 1981; Bell and dePolo, 1998),
- Rapid offsets in potentially ductile deposits and colluvial deposit on secondary faults appear to have been created earthquakes (dePolo and others, 2006),
- Deep aquifer input indicates the faults are deep rooted (Noack and others, 1998),
- Tilted panel between faults and inter-strike distance indicates deep intersection (dePolo and Taylor, 2005),
- Bifurcating fault patterns indicate propagation? (dePolo and Taylor, 2005).

Factors that indicate the fault scarps are created by earthquakes:

- Rapid paleo-surface offsets in potentially ductile deposits (dePolo and others, 2006),
- Colluvial deposit on paleo-fault scarp (dePolo and others, 2006),
- Possible lateral propagation fault patterns (dePolo and Taylor, 2005),
- Other supportive evidence (local microseismicity, possible local liquefaction, deep aquifer input – faults are open?) (dePolo and Taylor, 2005).

The first mention of sub-basin faults being associated with these scarps was by Plume (1984) who measured ~210 m of offset of the bottom of the basin across the Eglington fault using seismic reflection (see his plate 5). Langenheim and others (2001) used gravity measurements and drilling data to define the bottom of the Las Vegas Valley basin and modeled all the major scarps as having bedrock faults below them (see above figure). Most recently the direct imaging of fault offsets of the basement below scarps has been done using seismic exploration (Snelson and others, 2004 and 2005). Most, if not all, the major Quaternary scarps in Las Vegas Valley can be related to subsurface, bedrock faults.

A fortuitous 4- to 8-m-deep excavation into the footwall of Valley View fault exposed evidence for two, latest Pleistocene surface-rupturing events interpreted to be paleoearthquakes (dePolo and others, 2006). Although the excavation was across secondary faults, they offset the paleo-land surface by 2 to 3 m. The offsets were thought to be sudden because they formed a colluvial deposit in one case and appear to have

brittle offset in deposits that are capable of ductile deformation (dePolo and others, 2006). The most recent event occurred after about 14,500 ^{14}C ybp, but this is only a partial record because the main fault was not crossed (dePolo and others, 2006).

Microseismicity occurs in Las Vegas Valley, and historical earthquakes as large as M3.5 have been felt and broken windows in the valley (M3.5 1/8/89; M3.4 2/3/01). Several small earthquakes occur in and around Las Vegas Valley each year, especially in the western part of the basin.

Regionally there is late Quaternary extension occurring in southern Nevada as is indicated by late Quaternary faults. Although fortunately not with the density as further north, late Quaternary tectonic faults surround the Las Vegas basin. They are present to the west in Pahrump Valley (Pahrump Valley fault system), to the south-southwest along the east side of the Black Hills (Black Hills fault zone), and to the northeast along the eastern side of Moapa Valley (California Wash fault zone); each of these three faults has evidence of a Holocene paleoearthquake. Also at least one basin-bounding fault in Las Vegas Valley has always been thought to be tectonic because of its range-front position and geomorphic expression (Frenchman Mountain fault).

The Las Vegas Valley scarps are associated with tectonic faults and recent excavation exposures indicate these fault also have earthquakes. Based on microseismicity and surrounding Holocene paleoearthquakes, Las Vegas is in elephant country with respect to late Quaternary tectonics, and future earthquake activity along the Las Vegas Valley fault system is likely. The system should be scrutinized for earthquake potential, and a high priority placed on developing seismic hazard parameters for it.

Combination Hypothesis

The lack of definitive evidence of a clear cut dominant hypothesis causes many scientists to favor a combination tectonic–compaction origin to the scarps to mentally rationalize this uncertainty.

Although favoring a combination hypothesis can be cognitively satisfying, it doesn't promote resolving the issue. To honestly favor the combination hypothesis, one should believe that both processes are acting, not just that one can't rule either out, so both are possible. Further, when advocating a combination hypothesis, the percentage of deformation that is tectonic is needed to characterize the earthquake potential.

One fault of the system that bears some scrutiny as to additional processes besides tectonics is the Eglington fault. The fault has a relatively high proposed slip rate. On one hand the northeast-striking parts of the northern section are the most perpendicular to the local northwest-trending least-horizontal stress axis (c.f., Patton and Zandt, 1991; Anderson and O'Connell, 1993), potentially explaining their relatively higher rates inferred from higher scarp heights. On the other hand, many of these scarps are adjacent to the deepest parts of the basin, with the largest thicknesses of sediment to potentially

compact. An easy way to reduce the tectonic slip rate of the Eglington fault is to assert that some percentage is due to hydrocompaction. Nevertheless, although unusual, is the Eglington fault's slip rate prohibitive? We don't know a lot about paleoearthquakes along the Eglington fault, but we do know it has a very young event along it (<~2,000 years – Taylor, unpublished research). And we do know that the conditions to create significant hydrocompaction are difficult to achieve (see above discussion).

Summary of Driving Mechanisms

Evidence continues to mount that the Las Vegas Valley fault system is a tectonic fault zone that is partly responsible for forming the basin. Compaction of the sediments did not form a multiple kilometer-deep basin, tectonic activity did. The basin is surrounded by Holocene faults and has microseismicity, and it seems likely tectonic activity continues into late Quaternary. The tectonic control of the basin leads to the faults being boundaries between different thicknesses of sediments on either side. Thus, differential compaction enhancing these scarps is a possibility, but historical subsidence, which is likely occurring at higher than natural rates, has not caused any scarp formation. The relatively strong control on recent sedimentation and rapid offsets found on secondary faults support most, if not all, of the fault scarp development as being tectonic and formed by earthquakes.

Earthquake History

No direct determination of the earthquake history of the main fault traces of the Las Vegas Valley fault system has been made, but at least two paleoearthquakes have been identified on a secondary splay within the system (dePolo and others, 2006). These two earthquakes occurred around 14,690 ^{14}C ybp (14,210 – 17,020 cal ybp), and were probably only separated by hundreds to a few thousand years based on estimated sedimentation rates and a lack of soil development between the event horizons (an organic bearing layer was bulk dated). This is a minimum record because the main fault was not exposed.

Fault Slip Rates

No specific fault slip rates have been measured, except at the Eglington fault, which is discussed in a separate report. But it might be useful to have a sense of what fault slip rates for the Las Vegas Valley fault system could be. So here is a strawman calculation using rough modal heights for offsets and some guesses as to reasonable ages for those offsets. Near the north-central part of the system the Decatur, Valley View, and Cashman Field faults are subparallel and a composite slip rate can be made across them. A height of 6 m is used for the Decatur and Valley View faults and 18 m is used for the Cashman Field fault. The age of offset is just a guess and could be different for different faults. An estimate of 750 ky is used for the maximum age because the scarps would

likely be much more eroded if it was longer, and all faults, except the Eglington scarp, should have been going by ~80 ky. With a composite total of 30 m height over 750 ky to 80 ky, strawman rates of 0.04 to 0.4 m/ky are calculated for the system.

Earthquake Recurrence Intervals

No specific earthquake recurrence intervals have been reported. In this high risk setting, ideally conditional probabilities would be sought (meaning having a lot of paleoseismic data), but this may be impossible given the poor expression of faults and limited opportunities for exploration.

Earthquake Segmentation

No specific model has been proposed except to link the Decatur and Eglington faults together (Slemmons and others, 2001). Linkages and relatively short cross-strike distances between faults in the Las Vegas Valley fault system indicate multiple fault ruptures should be considered. There is no paleoseismic data on the main faults with which to judge contemporary events.

Single-Event Displacements

Unknown. An offset of about 30 cm vertical was measured on the most recent event known on the Eglington fault. Single-event normal dip-slip offsets of as much as 2 to 3 m were measured on a secondary fault of the Valley View fault (dePolo and others, 2006). No direct measurements have been made.

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Nevada Quaternary Fault Working Group **Eglington fault**
FAULT FORM

Pre-developmental photograph of the Eglington fault (photo by John Bell).

Fault Name

Eglington fault, part of the Las Vegas Valley fault system
USGS Fault and Fold Database Fault # 1733

Introduction

The Eglington fault is part of the Las Vegas Valley fault system, but has been singled out because it appears to have a higher rate of activity than most of the other faults in the system. The Eglington fault is entirely located within Las Vegas Valley and poses a distinct earthquake hazard to the northern part of that basin, especially the cities of North Las Vegas and Summerland. Prior to urbanization, the Eglington fault was expressed as a large, gentle warp (3º maximum tilt angle) in surficial deposits.

Location and Length

The Eglington fault is located in northwestern Las Vegas basin, in southern Nevada. The fault has an end-to-end length of 11 km (measured on Page and others, 2005; 1:250,000 scale geologic map) from an eastern truncation with a northwesterly striking structure (Las Vegas Valley shear zone) to a western end of the main trace of the Eglington fault; this is the same length as given by Zuckerman (1998). It is difficult to estimate a credible length shorter than this, but if the fault beyond the 300-m step at the eastern end is excluded, there is a continuous structure for about 9 km. A maximum value of 12 km can be estimated by extending the fault to the west of the zone of secondary faults or including the area between the Decatur and Eglington faults.

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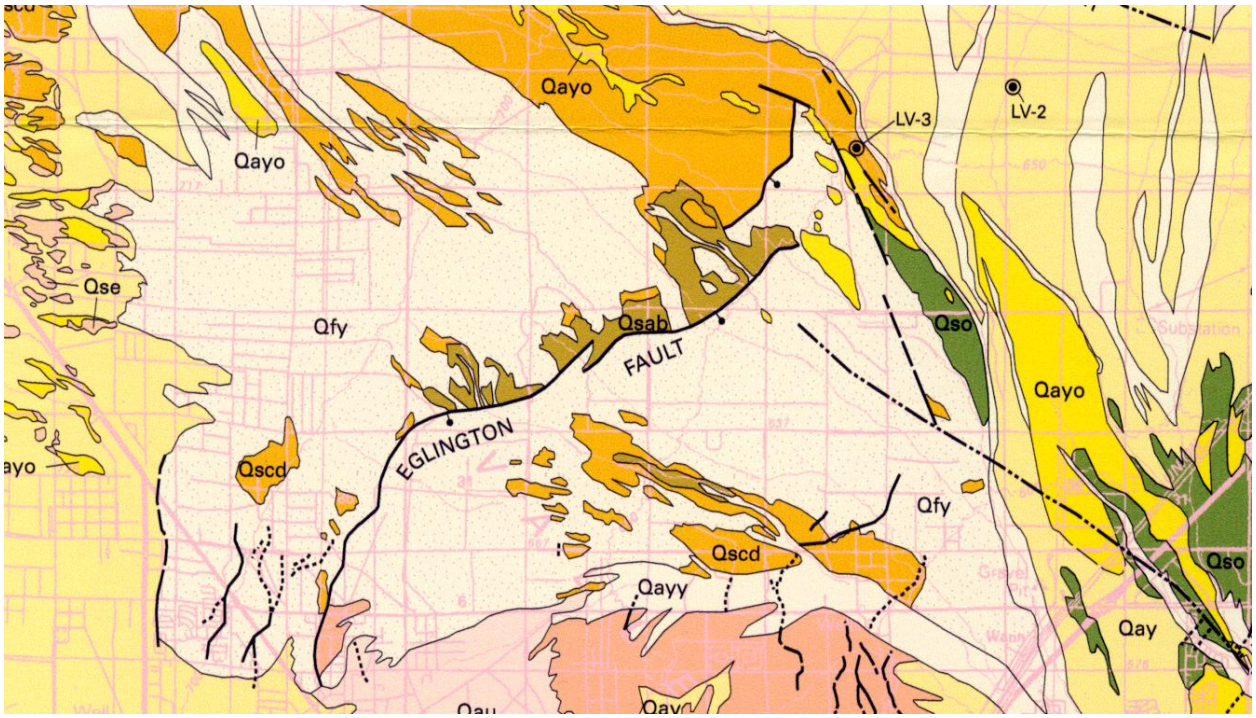


Geologic map of the Eglington fault (for scale: the end-to-end length of the Eglington fault is ~11 km, the small step in the fault has a cross-strike distance of ~100 m); map from Page and others (2005). Qfy – intermittently active fluvial fine-grained alluvium; Qayo – Holocene and latest Pleistocene alluvium; Qscd – latest Pleistocene fine-grained groundwater discharge deposits Units C and D; Qsab – late and middle Pleistocene fine-grained deposits; Qso – middle Pleistocene fine-grained spring deposits.

Geomorphic Expression

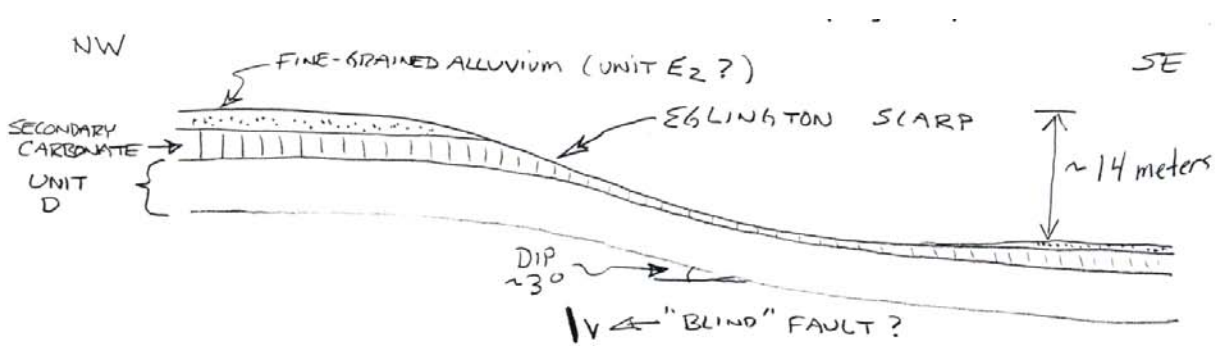
The Eglington fault has a spectacular expression in late Quaternary surfaces of Las Vegas Valley creating a large (as much as 25 m high) monoclinal warp isolating Gilcrease Flat from the downthrown side, Stewart Flat. Drainages have incised into the warp and for a short distance into the upper surface, but overall the warp and other features appear relatively uneroded and are easily seen on aerial photography. There are several vegetation lineaments on the warp, at least one that was proven to be a late Holocene fault by trenching studies. In one place (northeast of the intersection Ann Road and Decatur Blvd.) there is evidence of spring discharge near the base of the Eglington warp

that flowed long enough to build a small spring mound. Haynes (1967) and Zuckerman (1998) noted a northwest trending alignment of tufa features at the eastern end of Eglington fault as well.

Structural Description

The Eglington fault is a relatively short fault (~11 km) that is truncated at its northeastern end by the northwest-striking Las Vegas Valley shear zone (c.f., Nitchman and others, 1991; Zuckerman, 1998; Page and others, 2005), and may be the northern part of the Decatur fault zone (Slemmons and others, 2001); the two faults are aligned, but there is a break in continuity of the surface expression between the two faults that both faults splay into.

The Eglington fault is a major warp in deposits at the surface. The maximum angle of tilt measured on the sediments in the warp is 3º. A discrete fault zone is assumed to be within the basin and below, and only the upper sediments are likely folded; this is because the warp is a relatively narrow feature, 0.5 to 1 km in width. The fold may have been created by temporal variation in the activity of the fault. A decrease in fault activity allowed sediments to accumulate over the top, followed by renewed fault activity that is deforming these sediments. Alternatively there could be a plastic response of these sediments, perhaps earlier in latest Pleistocene when the flats were saturated with water.



Schematic cross section of the Eglington scarp between Centennial Road and Ann Road; from Nitchman and others (1991).

A number of small, discrete faults have been found on the Eglington warp, all of which have had offsets of 35 cm or less (Nitchman and others, 1991; Bell and dePolo, 1991, unpublished research; Taylor, 2006, unpublished research).

The fault is assumed to be a normal dip-slip fault, similar to other similarly oriented faults in the valley (c.f., Page and others, 2005).

Earthquake History

The most-recent event along the Eglington fault (PE1) occurred in late Holocene. A charcoal sample was collected by Dr. Wanda Taylor (UNLV) from a consultant's exploratory trench across a young fault near the base of the Eglington warp (the El

Campo Grande site). The sample came from a small colluvial wedge developed following the last event on that fault trace. The sample was submitted to Paleoresearch Laboratories for analysis, and 14 pieces of mesquite charcoal yielded a conventional radiocarbon date of 2,245 ±15 ybp. This date is calendar corrected at a two-sigma level to two time periods, 2,150 to 2,250 cal. ybp, or 2,300 to 2,340 cal. ybp. The sample was detrital, thus it could be an older sample being worked into a younger wedge. Also this age of sample is common in Las Vegas Valley, indicating it may be part of an event (e.g., wildfire event, climatic event; J. Bell, personal commun., 2006). Taken at face value, the date indicates that a surface-rupturing earthquake on the Eglington fault occurred around or just prior to 2,150 to 2,340 ybp, or a little over 2,000 years ago.

The fault exposed at the El Campo Grande site is synthetic to the Eglington fault, and may be a younger splay fault developing near the base of and cutting through the warp. Whether this surface rupture was a small event or part of a major event with additional displacement along the Eglington fault is not known.

The fault has been reactivated by subsidence deformation, but in an opposite sense-of-displacement than its tectonic movement because of where the subsidence basin is located (Bell and others, 2002).

Fault Slip Rates

Late Quaternary fault-slip-rate estimates for the Eglington fault are based principally on the offset of Unit D, the local surficial geologic unit that is warped across the fault. The assumption is that a brittle seismogenic fault lies below the warp a short distance below the surface, and the offset across the warp is the same as the offset below on the fault. Another assumption is that the age of this offset is also related to Unit D, beginning in the later part or following of the deposition of Unit D because the upper parts of the unit are involved in the warping. Thus, dates from Unit D are used to estimate the time of offset. A radiocarbon date collected by John Bell (NBMG) in 1991 from a pipeline excavation across the Eglington warp was also used.

Unit D, Its Age, and the Timing of the Offset of the Warp

The first definition, description, and dating of "Unit D", a local subdivision of the fine-grained deposits of Tule Springs, was done by Haynes (1967). Unit D is made up of light gray, gray, and light brown mud deposits with discontinuous layers and inclusions of organic-rich deposits, sands, gravels, and paludal (capillary fringe and spring fed) carbonate deposits (Haynes, 1967; Quade, 1986; Bell and others; 1998). Unit D crops out in the northern part of Las Vegas Valley and is as much as 8 m thick (Bell and others, 1998). It was formed during pluvial times in southern Nevada when the climate was much wetter, based on the character of the deposits, fossil evidence of local flora, and its age (Quade, 1986).

Haynes obtained radiocarbon dates on gastropods near the middle and base of the deposit of 22,600 ±550 ^{14}C ybp (UCLA-536) and 31,300 ±2,500 ^{14}C ybp (UCLA-462), respectively (also reported in Quade, 1986). Haynes (1967) considers these dates to be about 1,000 years too old considering other local gastropod-carbonized wood pairs. A carbonized wood sample near the base of the deposit was dated 25,300 ±2,500 ^{14}C ybp (UCLA-539). These dates are generally supported by more recent dating of Unit D, specifically four radiocarbon dates from the Tule Springs Park Quadrangle that range from 20 to 29 kybp (Bell and others, 1998) and five radiocarbon dates from the Corn Springs Quadrangle that range from 25 to 34 kybp (Bell and others, 1999). Quade (1986) estimated the age range for Unit D to be 15 to 30 ky old (based on uncorrected radiocarbon dates and sedimentation rates). The youngest age estimate is made by Quade (1986) considering the 1000-year correction to some of Haynes's dates and making a "rough estimate" of the sedimentation rate for Unit D; Quade also constrains this younger age by observing the oldest radiocarbon dates in the overlying "Unit E", which are about 14 ky. The youngest date from base of Unit E reported by Quade (1986) is 14,040 ±320 ^{14}C ybp, from a piece of carbonized wood at the base of a Unit E channel. This date calendar corrects to 15,871 – 17,877 cal. ybp.

In 1991, John Bell and Craig dePolo of the Nevada Bureau of Mines and Geology visited a pipeline excavation across the eastern part of the Eglington scarp at Centennial Parkway and found a charcoal layer in a small graben near the crest of the warp that post-dated a small offset (~30 cm on an antithetic scarp). This charcoal was sampled by John Bell and had a radiocarbon date of 18,690 ±170 ^{14}C ybp (GS-2958). This offset may be the early part of the modern phase of activity of the Eglington fault at this site.

The older radiocarbon dates of Haynes (1967) are too old to calibrate. Based on the calibration of Bell's 1991 date (18,690 ybp), these older dates could increase by about 3,000 years if they were calibrated.

Radiocarbon Dates Relevant to the Eglington Fault

Reference	Radiocarbon Date (ybp)	Sample #	Calibrated Radicarbon Date[1]
Haynes (1967)	22,600 ±550	UCLA-536	too old to calibrate
Haynes (1967)[2]	21,600 ±550	-	
Bell (1991) unpub. (~22)	18,690 ±170	GS-2958	21,803 – 22,613 cal. ybp
Quade (1986)[3]	15,000 ±500	-	(16,662 – 19,138 cal. ybp)[3]
Quade (1986)	14,040 ±320	W-5649	15,871 – 17,877 cal. ybp

1 – two-sigma calendar calibration using Stuiver and Reimer (1993) and Reimer and others (2004).
2 – modified from original: Haynes date minus 1000 years to account for the local chemistry of gastropods used in dating (Haynes, 1967; Quade, 1986).
3 - Quade (1986) made estimates of the age of the top of Unit D, but discussed ages in terms of radiocarbon years, not calibrated, so his estimated ages have been calibrated to get a better idea of the absolute time involved, and assigned a ± 500 year uncertainty to his values (half the time between Quade's constraints – 1000 years, and similar to errors from dates at the base of Unit E).

The best estimate for the time over which the Eglington warp was formed is ~22 ky, the rounded central part of the range of calibrated ages from Bell's 1991 date, with the presumption is that the warping started shortly before this. The range of possible time estimates (approximate two-sigma error range) is 15,870 ybp to ~25 kybp. The minimum estimate is the youngest estimate from the calibrated range of the dated sample from the base of Unit E, and the maximum age is taking Hayne's (1967) adjusted date of the middle of Unit D, approximately calibrating it by adding 3000 years to it, and rounding it off (22.6 k ybp – 1 ky (Hayne's correction) + ~ 3 ky approx. calendar correction). These age estimates should bracket the upper paludal part of Unit D.

Offset Estimates of Unit D

All the slip rates given in the literature on the Eglington fault have been based on estimating the age and offset of Unit D; these estimates have been 1 m/ky (Nitchman and others, 1991; dePolo and Ramelli, 1998) and 1-1.5 m/ky (Slemmons and others, 2001).

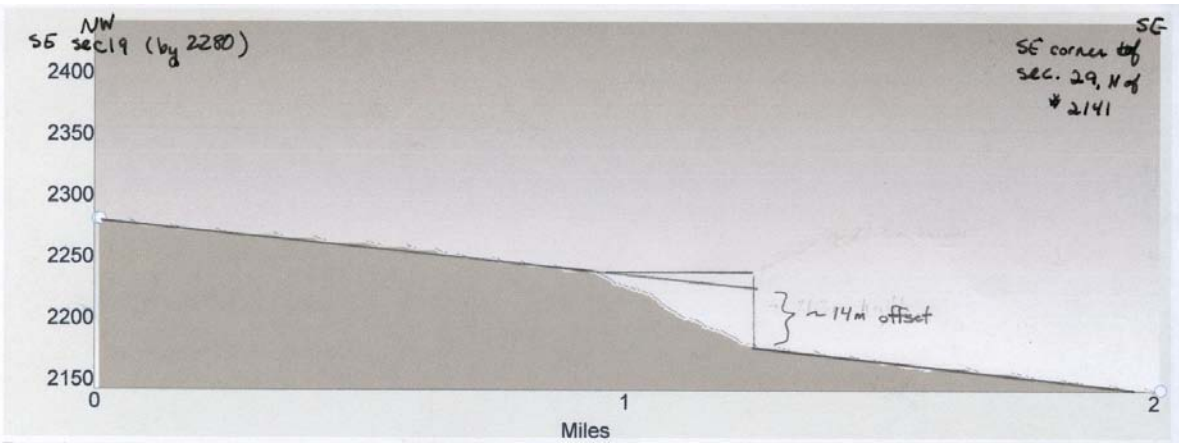
The vertical displacement of Unit D based on topographic offsets of the surface, maximum of about 25 m (Haynes, 1967), and in another location offset of a carbonate unit near the top of Unit D has been measured at about 14 m (Nitchman and others, 1991). Profiling the surface scarp from DEM's confirms a 14 to 25 m height to the Eglington warp (Taylor and dePolo, in prep.), with the highest scarp measurements only occurring over a small reach in the central part of the fault. Unit D is generally buried on the hanging wall. The general displacement profile of the Eglington fault is common of faults with a higher central portion tapering towards the ends of the fault, and supports a single-segment hypothesis for the fault (i.e., displacement is not the highest at the south end as it might be if it were part of a larger earthquake segment).

In the Ann Road area, a paludal carbonate layer near the top of Unit D could be seen in gullies to continuously warp down the scarp, and into the hanging wall with a fairly even thickness (~30 to 50 cm). It seems unlikely that this spring-related deposit would form with an even thickness if there were any significant escarpment present at the time of the carbonate formation, thus the monoclinal deformation followed the carbonate deposition, which is the upper part of Unit D (Nitchman and others, 1991).

Estimates of the height of the Eglington Scarp (Unit D) range from 14 to 25 m; Nitchman and others (1991) measured the 14 m minimum height, and Haynes (1967) and Taylor and dePolo (in prep.) measured a monoclinal warp height of ~25 m in at least one place along the fault, although there could be some erosion on the hanging wall potentially causing this value to be a little too large. The preferred offset estimate is 21 m; this is a solid maximum height measured by Taylor and dePolo (in prep.). Taylor and dePolo (in prep.) measured higher scarp measurements (18 m and 21 m) on either side of where Nitchman and others (1991) made their measurement, so a higher height value than 14 m seems likely.

The total offset across the fault scarp was estimated to be 14 m by dePolo and Taylor (in prep.) y projecting the upper and lower surfaces to the fault; see figure below. The

projection is matched over 1 km on these surfaces to help span the wide scarp more confidently. This measurement appears to be quite good, but 2 m is considered a potential measurement error, so the minimum offset is 12 m. The maximum offset possible is taken as 25 m, the largest scarp height measured by Haynes (1967) and assumes there has been significant burial on Unit D on the downthrown side.



Projected offset across the Eglington fault.

Unit D Slip Rate Estimates

Fault slip rate estimates for the Eglington fault are derived from the above preferred, maximum, and minimum values (Table 1). The dip of the Eglington fault is unknown, but with the many uncertainties involved, the vertical height of the warp serves as a reasonable proxy for the fault offset values, which would be slightly higher.

Table 1 Input values and late Quaternary slip rate estimates for the Eglington fault

Parameter	Best Estimate	Minimum Value	Maximum Value
Amount of offset	14 m	12 m	25 m
Time of offset	22 ky	25 to 30 ky	15.9 ky
Fault slip rate	0.6 m/ky	0.4 to 0.5 m/ky	1.6 m/ky

Older Slip Rate Estimates

Two older offset measurements along the Eglington fault have been made, 220 m of offset of the basement (Plume, 1984) and a 50 m offset of older basin sediments (Maxey and Jameson, 1948). The later offset, based on “driller’s logs” is hard to assign an age to for a rate, but is noted to only be two to three times larger than the offset across the

surface warp. A rough estimate can be made using the basement offset by considering the age of the basin opening as a constraint. The basin is of Miocene age, tens of millions of years old, and any slip rate derived from these values would be on the order of a ten thousandth of a m/ky; because this age spans multiple seismotectonic regimes, any derived slip rates from this older basement offset is likely not relevant for the modern tectonic regime.

The Eglington fault appears to be in an episode of activity that spans from latest Pleistocene to the present, which is consistent with the warped nature of the surface expression of the fault (sediments were deposited over the fault before it began to move during this recent episode). Subsurface offset measurements are only about half of the surface offset, consistent with a lower average rate of activity prior to latest Pleistocene.

Other Fault Slip Rates

The USGS Fault and Fold Database recommended a slip rate of < 0.2 m/ky for the Eglington fault because "the late Quaternary characteristics of this fault (overall geomorphic expression, continuity of scarps, age of fault deposits, etc.) support a low slip rate."

Earthquake Recurrence Intervals

No specific information on recurrence intervals is available.

Earthquake Segmentation

There is no strong reason to internally segment the Eglington fault; it appears to be a single structural or earthquake segment. There are only two steps in the scarp/fault that are 100 and 300 m in size.

A more important question is, should the Eglington fault be segmented from the Decatur fault zone to the south, or should these two faults be connected together as a compound earthquake segment? Subsurface reconstructions along the northernmost Decatur fault indicate the fault is well developed at depth, and likely coincides with a basement offset (Donovan, 1996; see section BB' on his page 104). The Eglington fault appears to be a single, continuous structure, although there are likely some complexities in the folding and faulting along strike. The northeast end of the Eglington fault is likely truncated by a cross fault at the Las Vegas Wash (Nitchman and others, 1991; Zuckerman, 1998; Page and others, 2005). This truncation may be important for understanding how the Eglington fault could have so much offset, yet be such as short structure (short-fat-fault problem). A cross-structure would allow a relatively large displacement on the main fault to approach its end and be accommodated. Late Quaternary displacement at the southern end of the Eglington fault appears to be distributed across multiple fault traces

and die out.

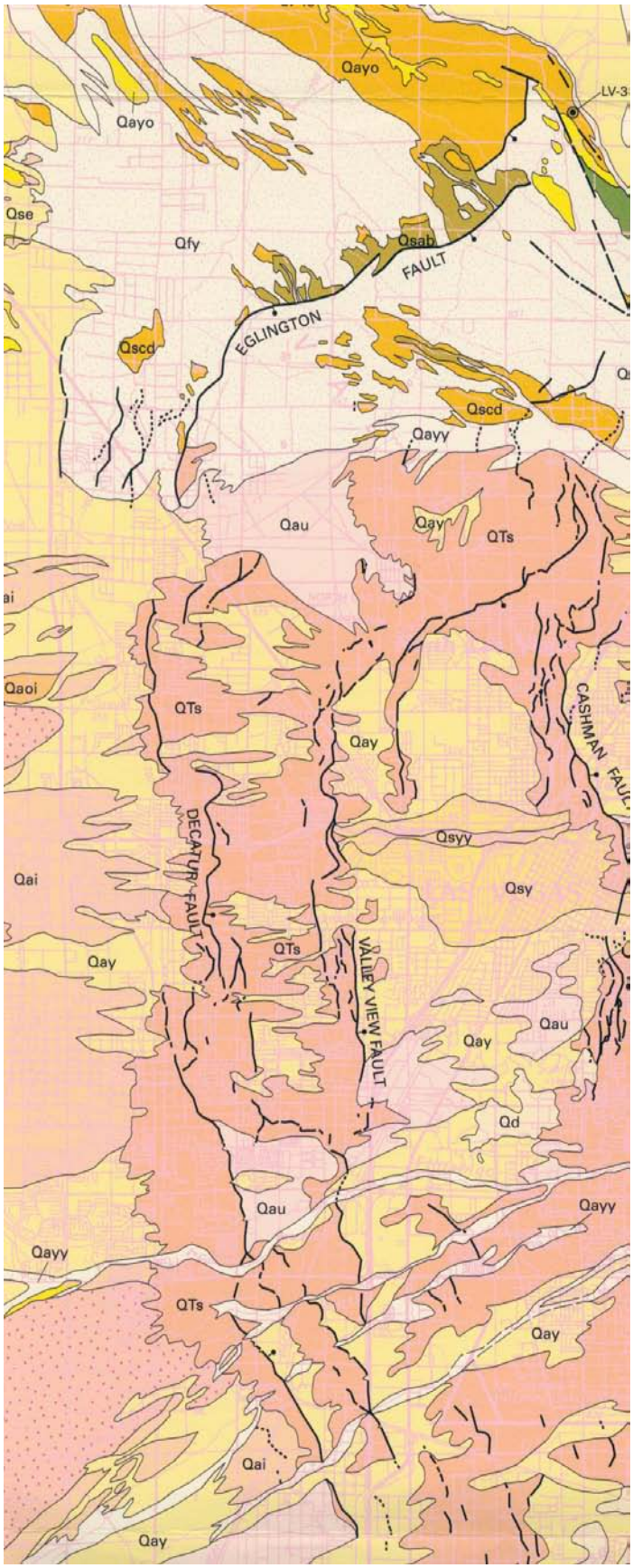
Single-Event Displacements

Only a minimum estimate of a single-event displacement is available from an offset along a single fault trace during the most-recent event(?); this vertical offset, 38 cm, is estimated from a displaced brown deposit in a consultant's trench; a colluvial wedge 20 cm thick formed against a small scarp above this offset (W. Taylor, unpublished research, 2006).

Comments

There has been debate over the origin of the Eglington scarp (and other faults within Las Vegas Valley). An early hydrocompaction hypothesis was forwarded for all faults within Las Vegas Valley by Maxey and Jameson (1948). This aseismic driving mechanism was adopted for decades, and little consideration was given to any seismogenic potential from faults within the valley. But several factors were inconsistent with this hypothesis, and a tectonic, seismogenic origin has been shown to be more consistent with existing data (Bell, 1981; Bell and dePolo, 1998; Slemmons and others, 2001; dePolo and Taylor, 2005; dePolo and others, 2006).

The largest inconsistency of the compaction hypothesis is that the amount of sediment thicknesses available to create differential compaction is not enough for the sizes of late Quaternary fault scarps and warps that exist (Bell, 1981). Another inconsistency is that bedrock offsets below the basin fill have been found below several of the faults, which should otherwise sole within the basin if they are only related to sediment compaction. In the case of the Eglington fault, 220 m of basement offset below the warp has been measured (Plume, 1984). Also in the case of the Eglington fault, there is not thought to be a change of sedimentary facies across the fault to create the setting for differential compaction; according to Haynes (1967) it crosses coarse alluvial fan deposits in the subsurface. This debate is discussed further in the Las Vegas Valley fault system report.



Geologic map of the Eglington and the Decatur faults.

Qfy – intermittently active fluvial fine-grained alluvium; Qay – young fan alluvium; Qayo – Holocene and latest Pleistocene alluvium; Qau – undivided Holocene and late Pleistocene alluvium; Qai – late and middle Pleistocene(?) fan alluvium; Qscd – latest Pleistocene fine-grained groundwater discharge deposits Units C and D; Qsab – late and middle Pleistocene fine-grained deposits; Qso – middle Pleistocene fine-grained spring deposits; QTs – gravelly basin-fill alluvium, Pleistocene to late Miocene(?).

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Nevada Quaternary Fault Working Group **Black Hills fault zone**
FAULT FORM

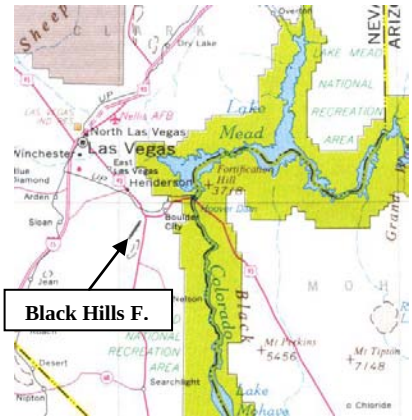
Fault scarp crossing the piedmont of the Black Hills (Photo by Larry Anderson, USBR)

Fault Name

Black Hills fault zone
U.S. Geological Survey Fault and Fold Database
Fault #116

Originally this fault was named the "Eldorado Valley fault" by Weber and Smith (1987) for a Tertiary fault that soled into a region detachment fault. To avoid confusion with the Tertiary fault when talking about a Quaternary fault that poses a contemporary seismic hazard Anderson and O'Connell (1993) referred to the Quaternary structure as the "Black Hills fault." Recent mapping by Fossett (2005) indicates four or more fault traces within the eastern piedmont of Black Hills, so the expansion of the name to "fault zone" is appropriate.

Location and Length



The Black Hills fault zone is located along the eastern flank of the Black Hills in southern Nevada, and is approximately 8 km west-southwest of Boulder City, 12 km southeast of Henderson, and 30 km southeast of Las Vegas. The Black Hills are a small set of hills in the northeastern part of the McCullough Range. The downdropped hanging wall of the Black Hills fault zone is Eldorado Valley.

Longwell and others (1965) noted that, "the steep east-facing escarpment in the northern part of the range [McCullough] reflects a normal fault extending southwest for a distance of more than 15 miles [24 km] from the vicinity of Railroad Pass." Anderson and O'Connell (1993) considered "the 10 – 12 km steep range front of the Black Hills to represent the late Quaternary surface length of the Black Hills fault." The Black Hills fault zone is part of a longer zone, as much as 29 km long, that continues south, bounding the eastern side of the McCullough Range, but this southern extension "is much more subdued topographically" (Anderson and O'Connell, 1993). The Black Hills fault zone has a remarkably short Holocene surface fault trace, approximately 4.5 km long (Anderson and O'Connell, 1993; Fossett, 2005).

Major Fault and Paleoseismic Investigations (chronological order)

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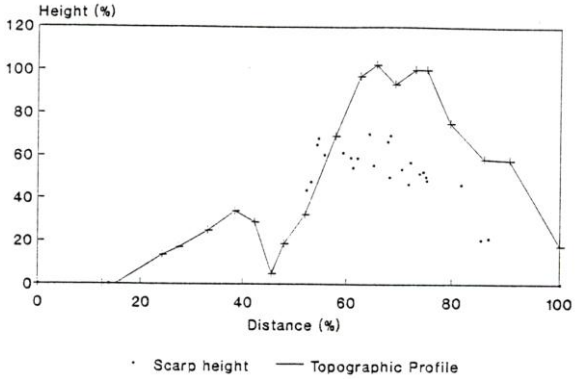
Geomorphic Expression

The Black Hills fault zone is a range-bounding normal fault, with down-to-the-east displacement, that is generally located at the mountain front-piedmont contact. The eastern escarpment of the Black Hills is very steep and pronounced. Details of the range front indicate a long history of movement with well-developed drainages, isolated spur ridges, and alluvial deposition within the mountain block. More recent activity is indicated by a series of fault facets and a tectonic trim line in the central part of the fault (a tectonic trim line is a height that facets reach and ridges are truncated at that defines the more recently active part of the range front). The highest fault facets along the range front are from 120 to 146 m high. Alluvial fans along the range front are steep and are covered with boulders, and have Holocene and latest Pleistocene age surfaces (Anderson and O'Connell, 1993).

The Black Hills fault zone is a group of faults shattering the piedmont, which widens towards the north; the width of the piedmont and the cross-strike distances between fault scarps in the zone increase together.

Fault scarps along the Black Hills fault zone have been examined and measured by Werle and Knight (1992), Anderson and O'Connell (1993), and Fossett (2005), and range in height from 0.5 m to 3 m and have maximum slope angles of 23º to 29º. The fault scarps along the zone are mapped as continuous across all surfaces except the active drainage deposits (Anderson and O'Connell, 1993; Fossett, 2005).



Werle and Knight (1992) measured 25 fault scarp heights along the Black Hills fault zone and found a general correspondence between scarp height and the relief of the Black Hills. Figure from Werle and Knight (1992).

Structural Description

The Black Hills fault zone is made up of several normal dip-slip faults, with down-to-the-east displacement. These form a zone with widths of 200 m in the southern part, widening to the north to as much as 1 km. Fossett (2005) mapped 14 fault traces that make up the Black Hills fault zone at a scale of 1:12,000. These fault races range from 75 m to 4.5 km in length. The dips of faults exposed in the trench are steep, but overall the faults in the zone may merge at depth to a shallower dip; this could be caused by reactivation of the older detachment fault which is roughly collocated with the Quaternary fault. Subsurface activation of this detachment may also contribute to the short length versus relatively large displacement character of this fault.

Earthquake Segmentation

Werle and Knight (1992) did an extensive review of a number of potential segmentation factors for the Black Hills fault zone, including changes in fault strike, transverse ridges and footwall salients, changes in mountain block relief, geophysical anomalies, and cross-fault intersections. They found the largest change in fault strike at the north end of the fault zone, where there are some older sediments cropping out that may be part of a transverse high (also the northern edge of the basin). A Bouguer gravity map, adapted from Bracken and Kane (1982), was used by Werle and Knight (1992) who noted two general gravity lows in Eldorado Valley, one adjacent to the Black Hills and one to the south. Between these lows is a gravity saddle high located near the southwestern end of the Black Hills (Werle and Knight, 1992). Werle and Knight (1992) suggested the possibility that this gravity saddle could be related to a buried transverse ridge, similar to some of Crone and Haller's (1989) observations of faults in Idaho and Montana. Cross faults were noted by Werle and Knight (1992) to be in the vicinity of Railroad Pass, at the northern end of the fault zone.

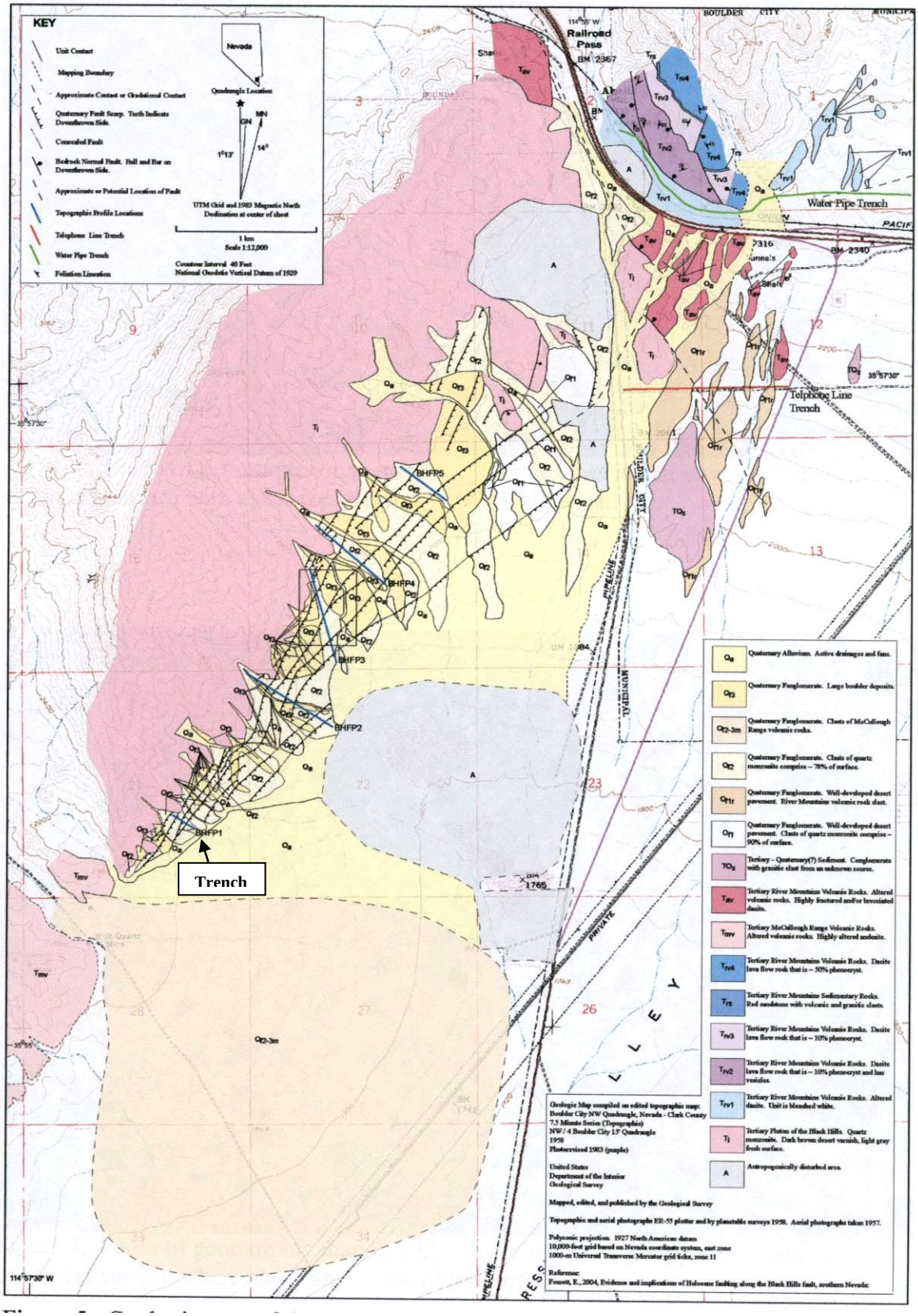
Based on their collective observations, Werle and Knight (1992) divided the overall fault zone along the eastern McCullough Range into two segments, a Black Hills segment [this report's name] and a segment to the south. The boundary between these two is the central perpendicular axis of the gravity saddle high, which intersects the fault zone just southwest of the southern end of the knolls, southwest of the Black Hills. The length of this segment is 14 km and the length of the segment to the south is 14 to 18 km (Werle and Knight, 1992).

Earthquake History

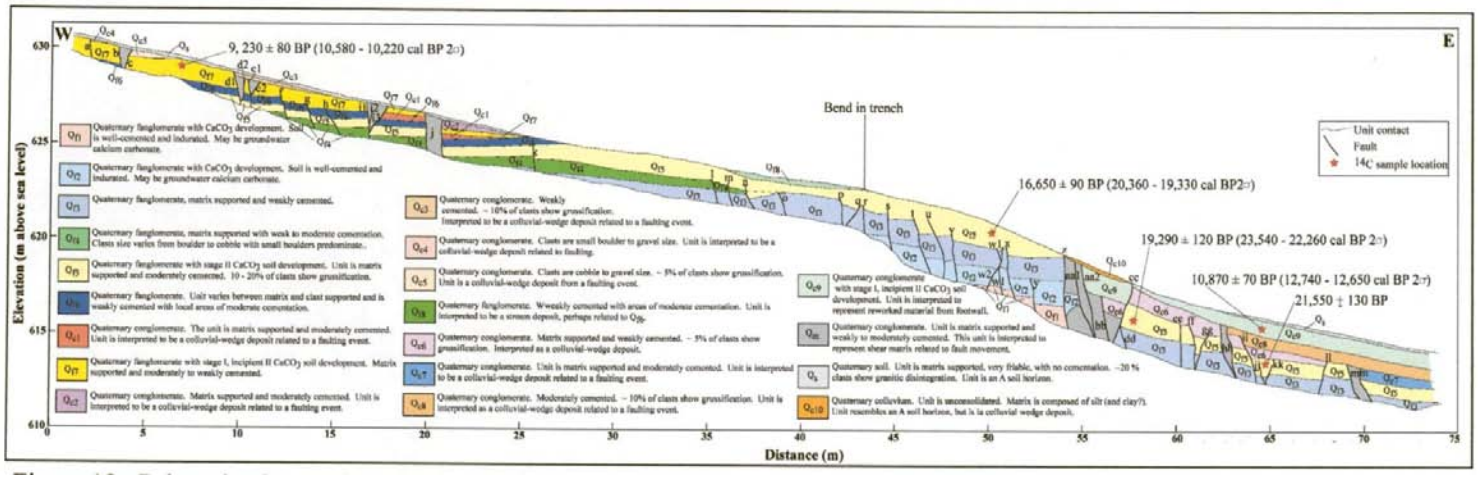
Several late-Quaternary surface-rupturing earthquakes have occurred along the Black Hills fault zone, including a Holocene event based on offset alluvial units, scarp morphology, and trench exposures. The earthquake history interpreted from trench is complicated because there are two fault zones and coincidences in timing are not clear in all cases (Fossett, 2005). Other problems encountered in the trench were similarities of deposits complicating unit correlations, and interpretation of faults observed to cut only part way into units (Fossett, 2005).

The earthquake history of the Black Hills fault zone is principally preserved along the main fault trace (lower fault) exposed by Fossett (2005) in a 75-m-long trench, located near the southern end of the Black Hills. A second, upper fault in the footwall contributes to this story, but does not, in the simplest interpretation, provide any additional events. At least one alluvial unit (unit Qf5) could be traced along most of the trench and used as a datum. The surface of the trench shows approximate far field slopes on the ends, a bulge in the footwall of the main fault, and a fault scarp at the main fault, with an apparent vertical offset of about 4.5 m. Some back rotation and graben formation complicate measurements on the main fault, and the upslope secondary faults actually have negative offsets when projected parallel to the far-field slopes, indicating there is likely a fault further to the west of the trench and these faults are in its hanging wall.

This review includes Fossett's (2005) original interpretations and an independent analysis conducted for this review. There are two fundamental differences between these interpretations: 1) Fossett (2005) used offsets measured at faults and this review projects all offsets parallel to far-field slopes to remove local deformation, such as rotation; this creates a little over a factor of 2 difference in total offset between the two studies, 2) A different date was emphasized for the earliest event and slip rate. The review uses Fossett's (2005) trench log and dates that were calendar corrected by Fossett (2005).



Black Hills fault zone as mapped by Fossett (2005).



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Trench log of the Black Hills fault zone made by Fossett (2005).

There are five paleoearthquakes interpreted along the main fault trace. Three events are interpreted along the upper fault trace, the youngest of which is thought to correlate with the most recent event along the main fault (PE1) and the oldest of which is though to correlate with the oldest event identified along the main fault trace (PE5?). There is evidence that the second oldest event (PE2) occurs on both faults, and that events PE3 and PE4 occurred on the main fault only. Enlargements of the trench log across these faults are included.

Paleoearthquake Chronology of the Black Hills Fault Zone

Event	**Timing Constraints**
PE1	2,250 – 10, 580 ybp
PE2	12,650 ybp – PE3
PE3	PE4 – PE2
PE4	PE3 – PE5(?)
PE5(?)	≈25,000 ybp

Paleoearthquake 1

The youngest paleoearthquake along the Black Hills fault zone is a major event activating multiple faults and offsetting the surface by ~1.5 m along one fault trace (Fossett, 2005). The event appears to have ruptured both fault zones exposed. This discussion will cover the evidence from the upper fault zone, the evidence from the lower fault zone, and the reasoning for correlating this event between the two zones, and other constraints on the age of the event.

Paleoearthquake 1 (PE1) ruptured at least five fault traces over a distance of about 23 m in the upper fault zone and created simple fault breaks (fault "a"), sheared or jumbled zones, and small upward-widening, triangular shaped shear zones, where the bounding faults merge within the trench exposure (Fossett, 2005). Small colluvial deposits (Qc3, Qc4, Qc5) also appear to have formed following small fault offsets. The datum for identifying PE1 offsets is a Quaternary fanglomerate unit (Qf7) that has been radiocarbon dated, and has stage I and incipient stage II carbonate soil development. The inorganic radiocarbon date is taken from a stage I carbonate rind and is 9,230 ±80 ybp (10,220 – 10,580 cal. ybp; Fossett, 2005). Because of the young soil on the deposit and the date, Fossett (2005) interprets unit Qf7 and PE1 to be of Holocene age. Fault offsets of the surface during PE1 across the upper fault zone totaled 1.75 m and the largest single trace offset was 1.12 m (Fossett, 2005). It is difficult to measure a projected net displacement for PE1 across the upper fault zone, however, because of apparent back-tilting, likely caused by displacement along an untrenched fault to the west.

The most recent event in the lower fault zone caused about 1.5 m of throw across fault "z" and antithetic fault "cc" (Fossett, 2005); these faults form a 2- to 3-m-wide, faulted graben. A thin layer of colluvium (unit Qc10) is deposited within the graben, covering fault traces. Down-faulted into the graben is unit Qc9, which elsewhere has an inorganic radiocarbon date from stage I carbonate in the uppermost part of the soil formed in the unit; the date is 10,870 ±70 ybp (12,650 – 12,740 cal. ybp; Fossett, 2005). Thus, the most recent event on the lower fault zone is likely younger that 12,650 to 12,740 ybp (Fossett, 2005). A projected offset across the lower fault zone for PE1 could not be made, mostly because there is no real datum to compare to on the eroding footwall and deposits were probably laid down on a scarp formed from earlier events. PE1 caused ~1.4 m of down-dropping of the colluvium from PE2 into the graben at the main fault, but the net vertical offset across the graben is only about 20 cm. Significant offset must have occurred in the shear zone between faults aa1, aa2, and z during PE1, creating a scarp that has since eroded back.

The simplest interpretation of the most recent events on the upper and lower faults is that they are the same event, PE1. The alternative interpretation is that there are two, separate Holocene events, possibly relatively close in time (PE1 and PE1.5).

Werle and Knight (1992) studied the Black Hills fault zone for a pipeline crossing and used scarp morphology studies to estimate the age of the most recent event. Werle and Knight (1992) measured 25 profiles across the young scarp and compared these empirically and using slope diffusion modeling. Their results are:

Technique	Age Estimation
Wallace (1977)	between 5,000 and 10,000 ybp
Bucknam and Anderson (1979)	between 9,000 and 14,500 ybp
Hanks and others (1984)[1]	between 5,500 and 8,200 ybp
Hanks and Andrews (1989)	approximately 5,500 ybp

1 – The initial slope used was 35% and a general Basin and Range Province diffusivity constant of 1.1 m^2/1000 years was used.

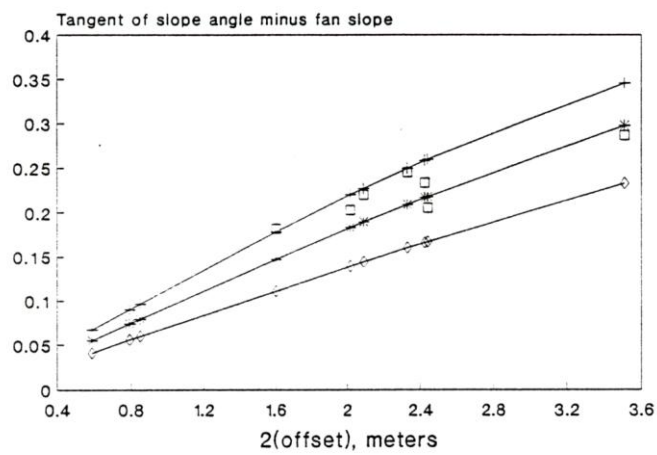


Figure 3. Fault scarp offset versus tangent of the scarp slope angle minus the fan slope (Hanks et al., 1984). Eldorado Valley fault scarp data (squares) as compared to modeled curves for selected ages: (+) 5,500 yrs.; (*) 8,200 yrs.; (diamond) 14,500 yrs.

Figure from Werle and Knight (1992).

Werle and Knight (1992) concluded the most recent event occurred <11,000 ybp (a regulatory comment), and that diffusion-equation modeling of scarp profiles indicated an age of between 5,500 and 8,200 years old. The morphological dating offers a lower age limit for PE1. Scarp morphology age estimates have uncertainties on the order of 50% (Hanks and others, 1984), thus the lowest calculated age of 5,500 ybp is halved to get a lower uncertainty limit, 2,250 ybp. There is some concern about the bouldery nature of the slope and scarp and Werle and Knight (1992) did not use the more armored scarps that appeared to be influenced by this and were less degraded. The fault scarp appears compound at Fossett's trench site and there is a question of whether it is compound where the scarp profiles were measured as well (Werle and Knight, 1992); this would tend to make these age estimates too old.

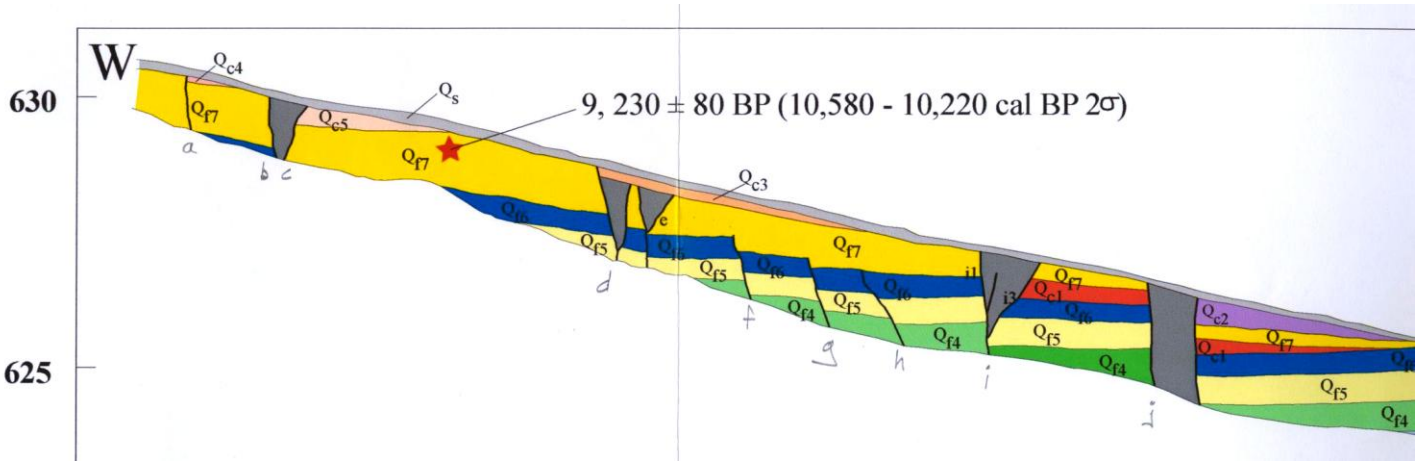
Anderson and O'Connell (1993) also measured scarp profiles and noted that:

> "Maximum slope angles of 23º and 29º suggest that this faulting event is quite recent, possibly within the last several thousand years. Two of the profiles plot between the regression lines for Fish Springs fault scarps (estimated age 2 ka) and the Drum Mountain fault scarps (estimated age 6-10 ka) and one of the profiles plots above the Fish Springs regression line."

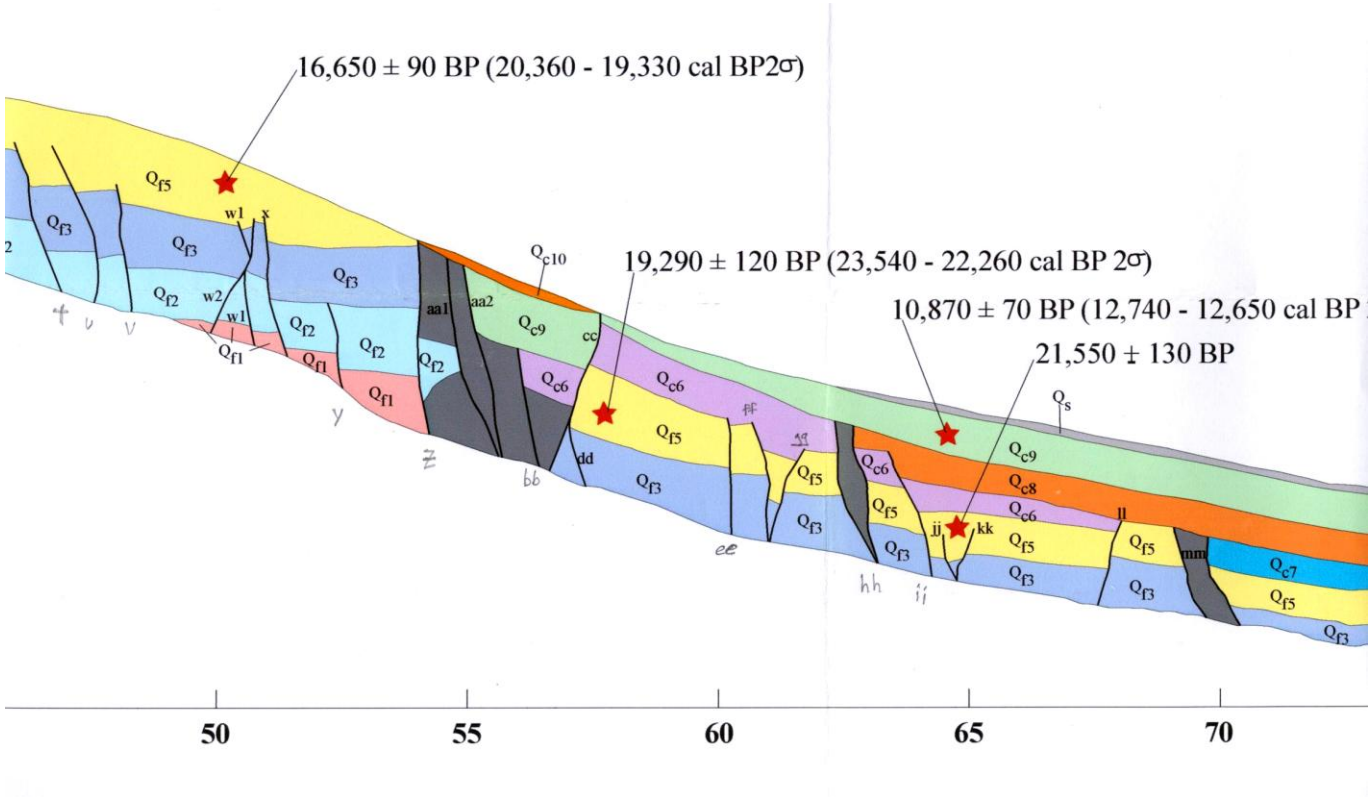
Observing the pattern of faulting across the bajada Anderson and O'Connell (1993) concluded, "considering the estimated age of both the displaced and unfaulted alluvial fans and the limited scarp profile data, the most recent surface faulting event on the Black Hills fault probably occurred during the mid to late Holocene."

Fossett (2005) suggested that the most recent events for the upper and younger fault zones are probably the same event, PE1, based on the similar maximum limiting ages and similar amounts and character of the overlying, post-event colluvium. Fossett (2005) also concluded that PE1 is a Holocene event (<11,500 ybp). The total vertical offset from PE1 is probably greater than 1 m, but is largely undefined because offset must have occurred on a fault to the west of the trench, and there is a lack of a specific datum that can be used across the entire trench. Fossett (2005) noted that there was about 1.75 m and 1.5 m of surface disruption for the upper and lower fault zones, respectively, during the most recent event.

The age of PE1 is bracketed between the upper end of the calibrated range for a radiocarbon date from a deposit faulted at the upper fault and the lower end of fault scarp degradation studies. The upper limit for the date in unit Qf7 is 10,580 cal. ybp. The lower age limit is the youngest age estimated from scarp profile modeling, halved to represent a 50% uncertainty, 2,250 ybp.



Upper fault zone (Fossett, 2005)



Lower fault zone (Fossett, 2005)

Paleoearthquake 2

Paleoearthquake 2 caused displacement on the main fault (lower fault zone) that subsequently formed a colluvial deposit (Qc9) downslope of the fault and preserved within a small graben structure (Fossett, 2005). This colluvial deposit is about 1 m thick within the graben and about ¾ m thick on the slope immediately downslope from the graben. Also within the graben, unit Qc9 is deposited on top of a shear zone that is associated with PE2, indicating that the deposit was formed just after the event.

Vertical offset from Paleoearthquake 2 was estimated by Fossett (2005) to be 1.98 m. Fossett derived the vertical displacement by "subtracting the measured throw of fault z (0.51 m), bb (0.93 m), and cc (0.98 m?) from the total measured throw of unit Qf5". Fossett (2005) did this to remove events unrelated to PE2 from the total offset, and to view the residual as the offset by PE2. It is difficult to project and get an offset for PE2 because of the lack of a datum on the footwall to measure from. The colluvial deposit associated with PE2 is of fairly even thickness and does not appear to be back-tilted. It is about ¾ m thick, which can be used as a minimum offset from PE2.

The middle event identified in the upper fault zone likely was coincident with PE2 along the main fault, but this is inferred and not constrained; thus it could have alternatively been coincident with PE3 or PE4, or in the extreme it could have been related to a separate event. The evidence for the middle event is the series of faults (faults f – h, and i1 – i3) that offset alluvial fan unit Qf6, and a colluvial deposit (Qc1) that overlies this deposit. The lower part of Qf7 may have been deposited just before this event because there are small fault contacts at the base between this and Qf6, but most of the deposit appears to fill an area that was back-tilted by PE2. Because of this back-tilting, it is difficult to estimate a net vertical offset for PE2 on the upper fault. Fossett (2005) added up all the small offsets along faults in the upper zone and estimates the offset of the surface from this event to be ~1.1 m.

The timing of PE2 is constrained by a non-organic radiocarbon date from stage I carbonate in the uppermost part of the calcic horizon formed in the unit; the date is 10,870 ±70 ybp (12,650 – 12,740 cal. ybp). PE2 occurred between 12,650 ybp and PE3, and is probably significantly younger than the oldest date in the trench, 21,550 ±130 ^{14}C ybp (~25,000 ybp). PE2 probably occurred on both the upper and lower fault zones, and had surface offsets of 2 to 3 m. The net vertical offset is difficult to estimate, but is likely at least ¾ m across the lower fault zone. Additional offset probably occurred on a fault to the west of the trench to create the back-tilting seen near the upper part of the trench.

Paleoearthquake 3

Paleoearthquake 3 occurred along two faults in the hanging wall of the main fault (lower fault zone), faults hh and ii. These faults offset a colluvial deposit from PE4 (Qc6) and have an associated buttressing colluvial deposit (Qc8). This colluvial deposit has a maximum thickness of ~0.8 m and the top of the unit is eroded, indicating a minimum offset of 0.8 m. Fossett (2005) measured ~1.45 m of throw across these faults during PE3.

The timing of this event is loosely constrained as occurring between PE2 and PE4, roughly between the broad constraints of 12,650 ybp and ~25,000 ybp.

Paleoearthquake 4

Paleoearthquake 4 occurred along the main fault and several faults in its hanging wall. Fossett (2005) interpreted that faults bb, ee – gg, ll, and mm all moved during this event, with all except fault ll being synthetic to the main fault; fault ll is an antithetic structure. These faults, except the main fault (fault bb) all offset fan unit Qf5, that blankets the site; fault bb also likely offsets Qf5, but materials in the fault zone are sheared beyond confident recognition (see trench log, Fossett, 2005). Two colluvial deposits are

associated with this event, unit Qc6 which is buttressed against fault bb (the main fault) and unit Qc7 which is buttressed against fault mm. Unit Qc6 also is buttressed against the antithetic fault, fault ll. Both colluvial deposits overlie unit Qf5 and underlie unit Qc8, and thus are stratigraphically correlative. Unit Qc6 has a maximum thickness of about a meter and unit Qc7 has a maximum thickness of about 0.6 m. The upper parts of these colluvial units are eroded off.

Fossett (2005) estimated the offset across fault bb to be a minimum of 93 cm based on the thickness of unit Qc6, measures ~74 cm of vertical offset across fault mm. Not a lot of back-tilting is evident in these deposits, thus these values may be both valid estimates of the surface offset and the net vertical offset.

The age of PE4 is partly constrained by radiocarbon dates in unit Qf5, which are older than the event. Three radiocarbon samples of stage I-II carbonate rinds were dated yielding results of 16,650 ±90 ^{14}C ybp, 19,290 ±120 ^{14}C ybp, and 21,550 ±130 ^{14}C ybp. The youngest date is deemed too young because it was from the footwall and likely spent a longer time in the wetting zone, whereas the other samples were buried earlier and removed from the wetting zone (Fossett, 2005). Fossett (2005) prefers the ~19 ky date because he believes it was appropriately isolated from younger material. It is not clear, however, why the ~22 ky date isn't a valid date, however, representing some of the potential spread in dates caused by using carbonate rinds for radiocarbon dating. Dr. Buck of the University of Nevada, Las Vegas (2007, personal commun.) agreed that using the oldest inorganic date from a unit should best approximate its deposition. Calendar correcting the ~19,000 year date yields a range of 22,260 – 23,540 cal. ybp (Fossett, 2005). The ~22 ky date is too old to be calendar corrected, but assuming it corrects to about 3 ky older gives an estimate of ~25 ky.

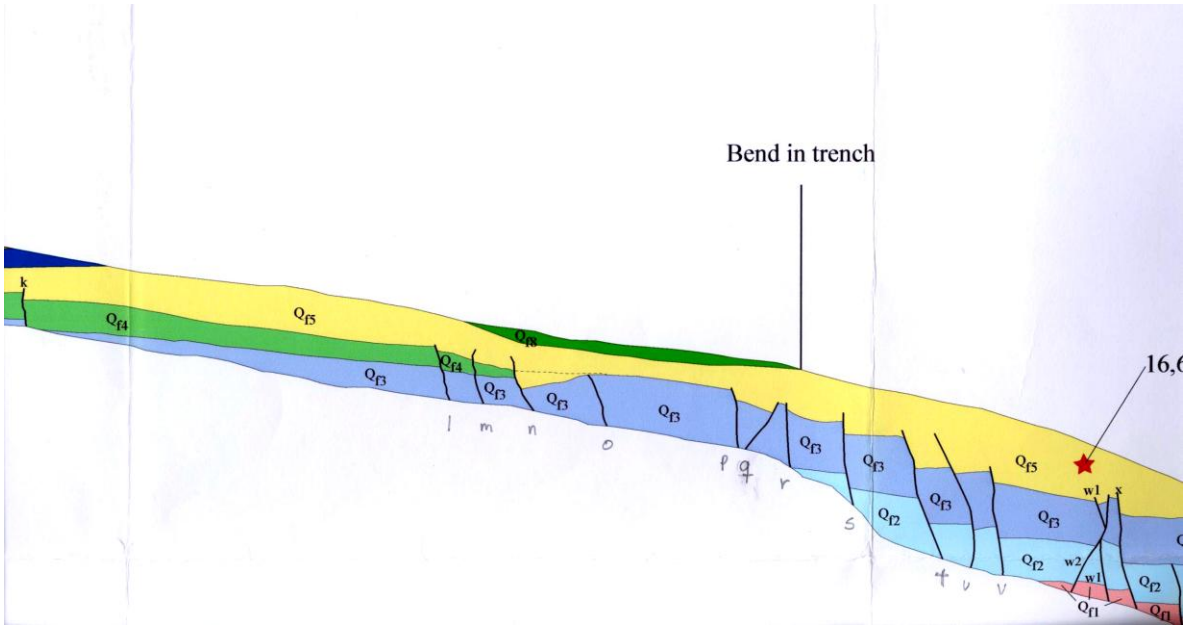
Thus, PE4 caused an estimated ~1.4 m of vertical offset at the trench site (Fossett, 2005). The timing of this event is loosely constrained as occurring between PE3 and PE5, roughly between the broad constraints of 12,650 ybp and ~25,000 ybp, but it is likely closer in time to the later time.

Paleoearthquake 5(?)

Evidence for a fifth possible event is a series of faults in the upper and lower fault areas that offset the base of unit Qf5 but do not extend through it. These include faults k – x in the upper fault zone and faults jj and kk in the hanging wall of the main fault zone. Any evidence of movement along the main fault or other larger faults in the upper zone has been largely overprinted or obliterated, but it seems likely that at least the main fault would have been involved in this event as well. Although one fault has nearly ¾ m offset, most of these faults have only a few to a few tens of centimeters of offset.

Fossett (2005) interprets that these faults are potential evidence for an event that occurs while unit Qf5 is being deposited. In the one place where the surface of unit Qf5 is preserved over one of these faults (faults jj and kk) there is no corresponding offset of the

surface, although there may have been some erosion. Alternatively the faults may have just died out in unit Qf5, although it is surprising that there are so many faults with this same relationship if that is the case. The fault tips could be deformation from bending that dies out upwards, but similar faults exist in the hanging wall of the lower fault as well, where there is less deformation. Fossett (2005) admits he does not fully understand the relationship between these faults and unit Qf5, but he believes movement along these faults is older that the other faults that moved during PE1-4 and was during the deposition of the Qf5 alluvium.



The middle of the trench log showing faults involved with PE5? (Fossett, 2005).

The total offset across these faults during PE5(?) was reported as ~3.1 m displacement by Fossett (2005). He referenced his trench log and his Table 2. Using a different approach to estimate this offset, the bottom of unit Qf5 was projected parallel to the far-field slope and parallel to the local slope, and in both cases anchored at fault z. The far-field slope projection gave a preferred minimum value of >0.5 m; this is the minimum because offset likely occurred on other faults. A projection where there is negligible offset is the minimum (>0 m) and a maximum value of >1.5 m is measured using the local slope (slightly shallower projection).

An estimate of 25,000 ±1,000 years is made approximate age of Qf5 and PE5(?) by taking the oldest date from unit Qf5 (21,550 ±130 ^{14}C ybp) and adding 3,450 years to it, for a rounded 25 ky; this is a correction that is similar to the calendar corrected amounts for the 19,290 ±120 ^{14}C ybp date. An uncertainty range of ±1,000 years seems like a reasonable approximation of an uncertainty on this (again based on the range in the calibrated ~19 ky dates).

The offset from PE5(?) is conjectural, but was probably >1.5 m, and maybe as much as ~3 m. In an alternative hypothesis these faults that die out in Qf5 were formed from a younger event (PE1 – PE4). In the few places the top of unit Qf5 is exposed over the dying out faults and is not offset, although there is a dip in the surface over fault n. If this was an event that occurred during the deposition of Qf5, the age of the event is ~25,000 ±1,000 ybp.

Fault Slip Rates

Fossett (2005) calculated fault slip rates using the oldest calibrated range from the second oldest date from unit Qf5 and the total throw measured in the trench; these are 23,540 cal. ybp and 12.965 m, respectively. Fossett (2005) noted that this time is a minimum because the carbonate was formed after the unit was deposited. Using these values gives a slip rate of 0.55 m/ky. To provide a lower slip rate value, Fossett used the displacement only from the lower fault zone (7.59 m) and the same date, 23,540 cal. ybp to get 0.33 m/ky. Fossett (2005) made a closed time interval estimation as well. He stated:

> "The most conservative slip rate estimate was calculated by adding all measured displacement in the trench (12.965 m), subtracting measured offset of faults from the oldest and youngest events (12.965 m – 5.905 m = 7.06 m), and dividing this total by the time between the oldest and youngest possible paleoearthquakes (23,540 – 9,230 = 14,310 yrs). This closed-interval method yields an estimated slip rate of 0.49 mm/yr, which is very close to the 0.5 mm/yr slip rate inferred from mountain-front sinuosity and valley-depth to valley-width method."

Thus, Fossett's (2005) range in slip rate for the Black Hills fault zone is 0.33 to 0.55 m/ky.

An independent slip rate was estimated using the timing information from the trench and a projected offset of the base of unit Qf5 to check Fossett's (2005) values. What is desired is to have the accumulation time period and the amount of release (fault offset from that accumulation), without open-ended intervals. Thus, the total time since PE5(?) minus the time since PE1 (present open-ended interval), gives the accumulation period for PE4 through PE1. By subtracting the offset of PE5(?) from the total offset, the offset of PE4 through PE1 is derived. The closed interval is made up of four accumulation periods and four offsets. The total time since PE5(?) is not precisely known because the date is too old to calendar correct. An estimate of 25,000 years is made by taking the oldest date from unit Qf5 (21,550 ±130 ^{14}C ybp) and adding about 3,450 years to it for a rounded 25 ky; this is an amount that is similar to the calendar correction amounts for the 19,290 ±120 ^{14}C ybp date. An uncertainty range of ±1,000 years seems like a reasonable approximation of an uncertainty on this (again based on the range in the calibrated ~19 ky dates). The range of time since PE1 is 2,250 to 10,500 ybp, thus, the accumulation time period for PE4 – PE1 is 13,500 to 23,750 yrs.

The total offset exposed in the trench is estimated by projecting the base of unit Qf5 across the trench log. The projection was made by anchoring a long straightedge on the base just east of fault "mm" and parallel to the upper and lower slopes away from the faults. This assumes that this straight projection approximates the original, undisturbed base of unit Qf5. This assumption seems reasonable to a first-order approximation, although unit Qf5 has variable thickness and the base, where exposed between faults, is only semi-even; thus, a projection uncertainty of ±1 m is used. The projected offset of the base is ~5 m, but offsets from faults "a", "b", and "d" are not accounted for (the base of unit Qf5 was not exposed across these). Offset across these faults adds ~41 cm to the total offset, using offset values from Fossett's (2005) Table 2. The projected offset is rounded to 5.5 m ±1 m. The offset from PE4 – PE1 is estimated by subtracting the offset during PE5(?) from the total offset. The minimum offset estimate for PE5(?) developed using the far-field projection and a maximum offset local projection is >0 – >1.5 m, where the greater-than sign indicates other possible offset on faults (see PE5(?) discussion; this has only a minimal impact on the slip rate estimate because the fault to the west of the trench doesn't enter into these calculations and the offset on the lower fault can be constrained to being small by considering the total offset and offsets from later events). After removing PE5(?), the vertical offset from PE4 – PE1 was 3 – 6.5 m.

Thus, using the projected net offset of 3 – 6.5 m for PE4 – PE1 and the accumulation time of 13.5 – 23.75 ky, gives a vertical slip rate estimate of 0.1 – 0.5 m/ky over four seismic cycles. These values are similar, although a little smaller, to Fossett's (2005) values; one of the fundamental differences is that the rates developed here are smaller because they account for some of the near-surface rotation and tilting by using a projection. For a perspective of what impact the minimum nature of offsets for PE5(?) could have, if an additional 1 m of offset occurred on other faults during PE5(?), the slip rate range would be reduced to 0.09 to 0.4 m/ky.

DePolo (1998) estimated a reconnaissance vertical slip rate of 0.3 m/ky based on maximum basal facet height and an empirical relationship. Anderson (1999) placed the fault in the "less than 0.2 mm/yr" category because the "late Quaternary characteristics of the fault (overall geomorphic expression, and lack of evidence supporting multiple faulting events, etc.) suggest the slip rate during this period is of a lesser magnitude [than the rate indicated by fault facets]."

Earthquake Recurrence Intervals

Several paleoearthquakes have been identified along the Black Hills fault zone making an estimate of the average earthquake recurrence interval possible. Fossett (2005) estimated an average recurrence interval from the trench data of 4.7 ky (3.6 – 10.2 ky); the maximum value is the maximum time since PE1. Fossett (2005) noted an inconsistency between these values and the model rate of ~1 to ~3 ky considering displacements correlated to magnitude estimates and slip rates. With the given data from trenching, these model recurrence intervals are too short (Fossett, 2005).

The accumulation period developed in the preceding section can be divided by the number of events for that period (four) to estimate the average recurrence interval. The accumulation period is 13.5 – 23.75 ky, yielding an average interseismic interval of 3.4 – 5.9 ky. If PE1 occurred in mid- or early Holocene, then roughly a full average accumulation period has passed since the last event.

Single-Event Displacements

Single-event offsets are difficult to measure at the trench site because of a common lack of through-going datums, difficulty in understanding original slopes for projection, and the possibility of additional, untrenched faults. Vertical offset estimates during paleoearthquakes from the trench range from 1 to 1.4 m, but should be considered minimums.

Anderson and O'Connell (1993) measured surface offsets of 1.8 to 2.8 m across fault scarps from the most recent event.

Critical Assumptions

Many of the above arguments and estimates are based on inorganic radiocarbon dates on stage I carbonate. If the dating of the oldest unit is too young, many of the above values would have to be adjusted. This is a critical assumption.

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